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FINAL REPORT
ATMOSPHERIC TETHER MISSION ANALYSES

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FOREWORD

This report is submitted to the George C. Marshall Space Flight Center by Lockheed Martin Astronautics in response to the requirements of Purchase Order H-27245D "Atmospheric Tether Mission Analyses".

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1.0 Introduction/Executive Summary

NASA is considering the use of tethered satellites to explore regions of the atmosphere inaccessible to spacecraft or high altitude research balloons. This report summarizes the Lockheed Martin Astronautics (LMA) effort for the engineering study team assessment of an Orbiter-based atmospheric tether mission. The study was led by the George C. Marshall Space Flight Center (MSFC) Program Development organization. Lockheed Martin responsibilities included design recommendations for the deployer and tether, as well as tether dynamic analyses for the mission. The period of performance for the LMA effort was July through September 1996.

The study was driven by requirements received from the atmospheric mission science definition team. The top level requirements for the mission are summarized below:

- Tethered endmass with science instruments to be deployed downward from Orbiter
- Mission duration of 6 days
- Endmass to spend 2 days at or near each of the following altitudes: 170 km, 150 km, 130 km
- Full retrieval/recapture of endmass not required

The deployer concepts considered during the study included the Tethered Satellite System (TSS) reel deployer, the Small Expendable Deployer System (SEDS), and a hybrid concept which combines the deployment characteristics of a SEDS with a reel for tether retrieval capability. A trade study was performed to evaluate the concepts in terms of flight experience, required development and testing, Orbiter safety issues, schedule, cost, deploy/retrieve capability, and operational complexity. It should be noted that although full retrieval of the endmass was not a mission requirement, partial tether retrieval offers advantages for endmass altitude control, therefore retrieval capability was considered among the evaluation criteria. The results of the trade indicated that the TSS Deployer with limited modification, is the recommended design for the atmospheric mission (reference section 3.1.2 for more detailed information on deployer selection).

Three tether configurations including single line, multistrand (Hoytether) and tape designs were studied. The key criteria for tether selection were flight experience, strength, required development, manufacturability, deployability and survivability. Tether survival probability was a major issue considered during the study. Although the multistrand design offers the highest survival probability, a significant development effort is required to fabricate and demonstrate deployability of long-length multistrand tethers. The baseline tether selected in the study consisted of a single strand design, due to its relative ease in manufacturing, deployability and high breakstrength. Additional information on the tether trade study is contained in section 3.1.1.

Multiple tether dynamic profiles were run to assess tether length, rate, tension, libration and Orbiter propellant requirements as a function of time for the atmospheric tether mission. Two mission scenarios were addressed and are described below:

1) Baseline Scenario - Orbiter/endmass altitudes maintained by Orbiter thrusting

Orbiter enters 220 km orbit

Mission Day 1

- Tethered endmass deployed downward 50 km to 170 km altitude

Mission Day 3

- Additional 20 km tether deployed, endmass at 150 km altitude

Mission Day 5

- Final 20 km tether deployed, endmass at 130 km altitude

Mission Day 7

- Cut tether, endmass reenters atmosphere

2) Optional Scenario - Endmass altitude maintained by partial tether retrieval/Orbiter thrusting

Orbiter enters 280 km orbit (Mission Day 1)

- Tethered endmass deployed downward 110 km to 170 km altitude
- Retrieve 15 km tether length over 2 day period
- Final deployed tether length 95 km

Orbiter at 265 km orbit (Mission Day 3)

- Tethered endmass deployed downward 20 km to 150 km altitude
- Retrieve 25 km tether length over 2 day period
- Final deployed tether length 90 km

Orbiter at 240 km orbit (Mission Day 5)

- Tethered endmass deployed downward 20 km to 130 km altitude
- Combine tether retrieval/Orbiter thrust to maintain 130 km endmass altitude

Mission Day 7

- Cut tether/endmass reenters atmosphere

The baseline scenario makes use of tether deployment only (no retrieval) to maneuver the endmass to its required altitudes, at the expense of increased Orbiter propellant usage for altitude maintenance. While the baseline scenario seems to offer a simple operational approach, further study is required to determine impacts on libration and other tether dynamic responses during frequent Orbiter thruster firings.

The optional scenario makes use of both tether deployment and partial retrieval operations to control endmass altitude. While slightly more complex than the baseline scenario, this option decreases the Orbiter propellant requirements significantly and also offers higher fidelity control of endmass altitude.

2.0 Scope

The scope of the LMA effort is defined in the Statement of Work for Research Entitled "Atmospheric Tether Mission Analyses" as part of MSFC Purchase Order H-2724D Attachment 1 (included in Appendix 5.2 herein). To summarize, LMA was responsible for recommending deployer and tether design concepts for the atmospheric tether mission (ATM), and performing the necessary tether dynamics analyses to evaluate overall tether system control. LMA also participated in several technical telecons with the MSFC-led study team on the subjects of endmass design and science instrument requirements.

3.0 Contractor Tasks

The study tasks performed by LMA are described in this section. Paragraph numbering corresponds to the numbering scheme in the aforementioned Statement of Work (Appendix 5.2).

3.1 Tether and Deployer Concept Definition

3.1.1 Tether Concept

Tether geometries addressed during the study included single strand, multiple strand (also referred to as Hoytethers) and tapes. The study initiated with a baseline single strand tether design agreed to by the engineering team. The single strand design consists of a Kevlar strength member (1.65 mm diameter) and outer Nomex jacket (2.16 mm final OD), with a breakstrength rating of 2892 N, as shown in Figure 1. The mass per unit length of the tether is 4.03 kg/km. This baseline was selected due to its large safety margin over the maximum expected mission loads (approximately 350 to 400 N) and its compatibility with the existing TSS deployer mechanisms. In addition, its manufacturability has been proven (LMA had samples of this tether fabricated at a subcontractor facility in the early 1980s). The materials used in this tether have heritage usage on the TSS conducting tether; no new materials have been found that would substantially improve this design in terms of environmental resistance.

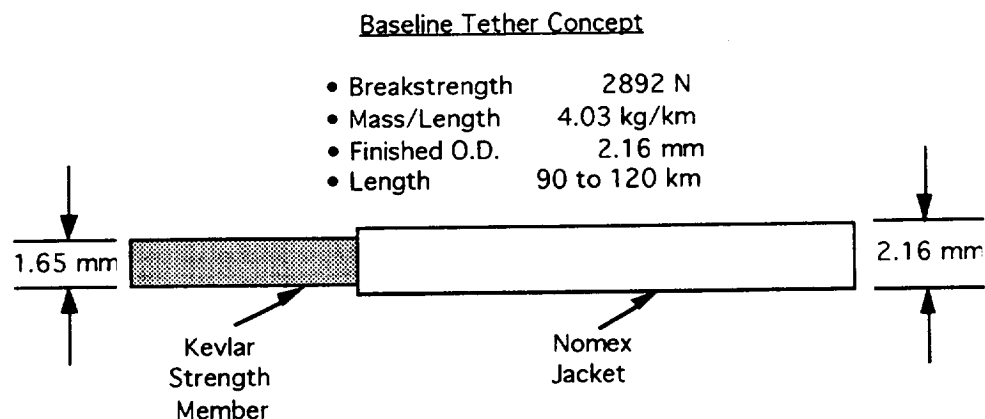


Figure 1 Baseline Tether Concept - Single Strand Design

The Lockheed Martin team participated in discussions/studies of alternate tether concepts (Hoytethers) with R. Forward of Tethers Unlimited and S. Pavelitz of Sverdrup. Specific issues focused on survivability and strength rating comparisons between the baseline design and Hoytether designs. One exchange of e-mail discussed sizing single strand tethers and Hoytethers based on standard space structural requirements. An analysis of drag areas for a single strand tether with a safety factor of 4X to a Hoytether with a safety factor of 2X is included in Appendix 5.2. The single strand tether was more efficient in drag reduction for equivalent strength rating.

The study addressed tether materials, especially pertaining to atomic oxygen requirements. No materials have been identified that will dramatically improve performance of the proposed Kevlar/Nomex single strand tether. Post-flight inspections of the TSS conducting tether, which also used Kevlar and Nomex, indicated no visible environmental degradation effects. Atomic oxygen resistant Hoytether materials were also discussed; glass with Teflon lashings were identified as the present candidate materials. Spectra was deemed unsuitable due to its sensitivity to atomic oxygen. An overbraid layer is impractical to fabricate with the Hoytether multiple strand configuration, therefore the strength member elements themselves must be able to withstand the atomic oxygen environment.

The team performed a Kepner Trego (K-T) evaluation of single strand, Hoytether, and tape tether designs. Results are provided in Table 1. Impact survival was given the highest weighting factor (10), followed by strength (9). Thus, mission success, in terms of tether impact survivability was given the highest priority. Deployability, manufacturability, and development needed were each assigned a weighting factor of 8. Test simplicity, thermal properties, atomic oxygen resistance, and flight experience were also important considerations.

Characteristic	Weighting	Hoyt	Single	Tape
Flight Experience	7	1	3	2
Development Needed	8	2	9	4
Manufacturability	8	3	9	5
Strength	9	5	5	5
Deployability	8	3	10	5
Retrievability	3	2	10	4
Impact Survival	10	10	2	8
Atomic oxygen	7	4	7	7
Thermal	7	4	8	2
Aerodynamic Drag	5	4	6	2
Twist	3	3	8	4
Lead Time	4	2	10	4
Testing	7	1	7	3
Total		322	588	385

Table 1: Kepner Trego Analysis of Tether Configuration Options

The Hoytether was highly rated for impact survival. It generally rated lower than the single tether for other categories. It was rated low for development relative to the single strand because of the extensive work still required to manufacture long lengths and to develop suitable spacers in the tether. Deployability also received a low score because of spacer/mechanism compatibility issues. Twisting of the Hoytether received a low rating because twisting would cause the strands to cross, inducing points where a single impact could rupture all strength elements. Atomic oxygen was given a median score based on discussions of constructing a Hoytether with glass elements. Thermal characteristics were considered low due to concerns for the high temperature strength of the proposed Teflon whipping used in the tether. One manufacturer rates its Teflon thread to 288 °C, but non-filled Teflon is known to creep when subjected to stress. Further evaluation of the whipping material is required.

The single strand baseline tether scored high for deployability, retrievability, lead time, and manufacturability. Development was rated high because samples have been fabricated and tested. Environmental factors are also high for the baseline tether design. Flight experience was considered low because of the baseline tether strength member similarity to the TSS-1R conducting tether. This was a conservative judgment call since the failure was a result of an electrical arc through the tether conductor insulation, and not a result of pure tensile overload. The arc eventually burned away the Kevlar strength member leading to a tensile failure. The baseline tether still received the highest score overall despite the low score assigned for flight experience. Impact survival is also lower than the Hoytether, although present estimates are for a >93% survival probability for a 6 day mission.

The tape tether rated high for impact resistance. Manufacturability was near the median because it appears more straightforward than a Hoytether. Thermal properties and drag effects were rated low because of the asymmetric tether shape. Testing received a low score because of the extensive effort required to prove a new mechanism design for a tape tether configuration.

Tether Design Recommendation:

The trade study results indicated that the baseline single strand tether is the preferred design in terms of high performance rating and minimal development effort. The concern about micrometeoroid and orbital debris impact survivability for this design has been mitigated by recent impact calculations, which show a survival probability > 93% for the six day mission. This is considered a reasonable number compared to the other uncertainties in this mission. Deployability of single strand tethers has been verified on TSS, SEDS, and NRL tether missions. LMA recommends the single strand baseline Kevlar/Nomex tether for the atmospheric tether mission.

3.1.2 Deployer Concept

Three deployer types were examined during the study: reel (TSS deployer and reel tape deployer), spool (SEDS), and a reel-spool hybrid. In addition, auxiliary capabilities and compatibility such as flyaway method and Orbiter safety considerations were addressed.

The first reel concept addressed was the existing TSS deployer shown in Figure 2. The prominent elements of the TSS deployer include a reel/level wind assembly and satellite support structure. The deployer is designed to mount to a Spacelab Enhanced Multiplexer/Demultiplexer Pallet (EMP). Avionics boxes are located throughout the EMP to provide power, control and telemetry for the deployer mechanisms. The lower and upper tether control mechanisms (LTCM and UTCM, respectively) are used to route and control tether movement off of the reel.

This system was originally designed to accommodate an atmospheric mission with minor modifications. The reel is adequate for approximately 120 km of single strand tether, and the brake mechanism can apply the necessary torque increases with a spring changeout. The reel motor and associated Motor Control Assembly (MCA) must be modified to account for the increased current caused by the longer tether/increased tensions. Tensiometers in the LTCM and UTCM are recommended to be changed for the higher tensions, although the UTCM tensiometers may be used as-is to yield better mid range resolution.

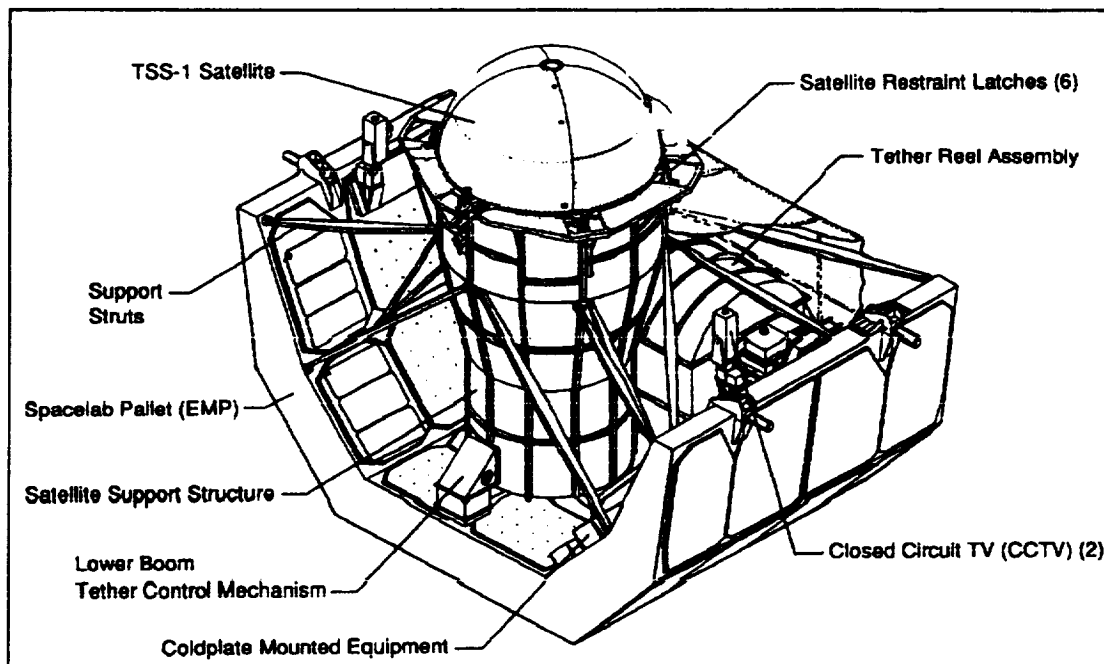


Figure 2 Tethered Satellite System (TSS) Reel Deployer

An alternate reel packaging concept in which the tether path is parallel to the reel axis was also examined (see Figure 3). Depending on the specific mission requirements this concept could have the encoder, vernier motor, and tensiometer integrated onto the level wind mechanism yielding a very compact package. This geometry could also be used to repack the existing TSS hardware on a new structure. This parallel axis design could also deploy and retrieve tape tethers. Either reel concept would be compatible with a deployable boom.

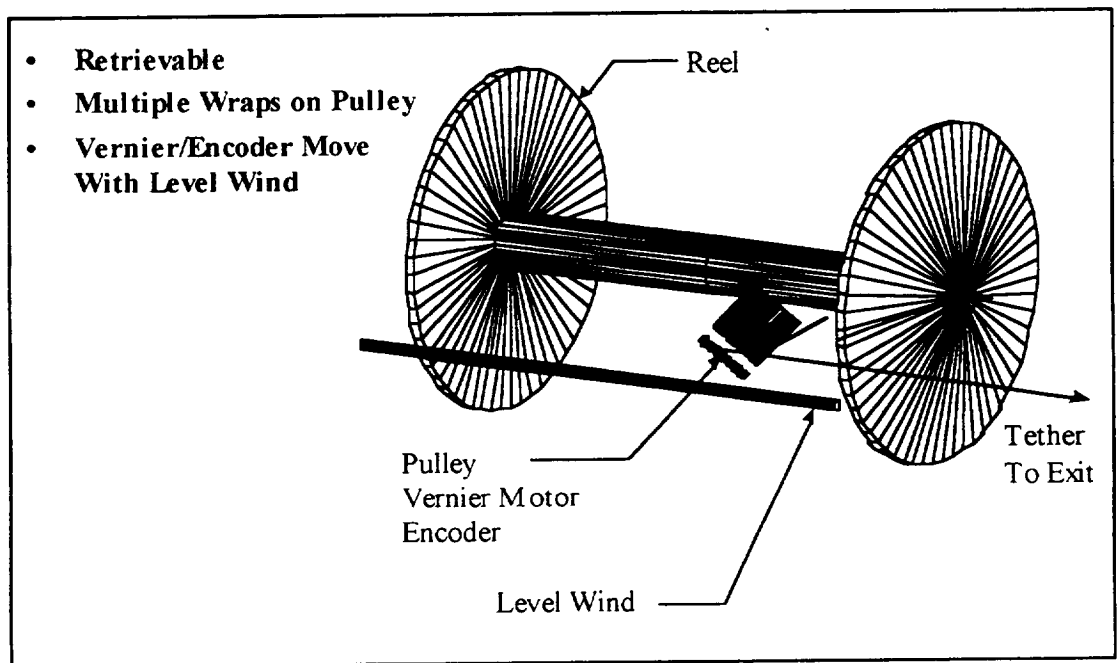


Figure 3 Alternate Reel Packaging Concept

The reel-tape concept is an extremely simple, low tension deploy-only tape deployer, as shown in Figure 4. The tape passes between two motor driven rollers that strip the tether off of the reel. The reel has a drag brake to provide inboard tension. An encoder is mounted on the reel shaft. No level wind is needed as the system does not retrieve tether. This system is not compatible with a deployer boom.

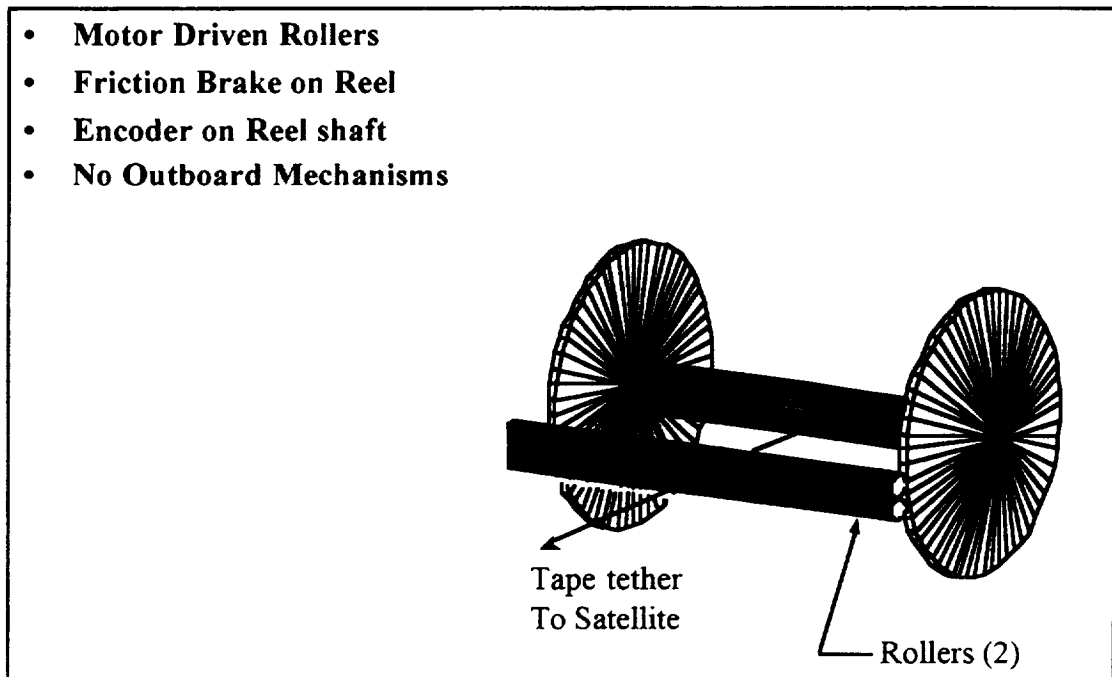


Figure 4 Tape Tether Deployer

The spool deployer is a standard SEDS design scaled up for the ATM. Scaling would include increasing the spool volume to wind a longer, larger diameter tether, and modifications to the brake to provide more friction and to dissipate the braking energy. This concept has no deployable boom.

Figure 5 depicts the reel-spool hybrid which consists of a reel deployer with an outboard SEDS-type spool. Initial spring deployment would strip tether off of the spool until outboard tension was greater than inboard drag forces. The deployment sequence would then transition to a reel-controlled strategy for higher tension or retrieval operations.

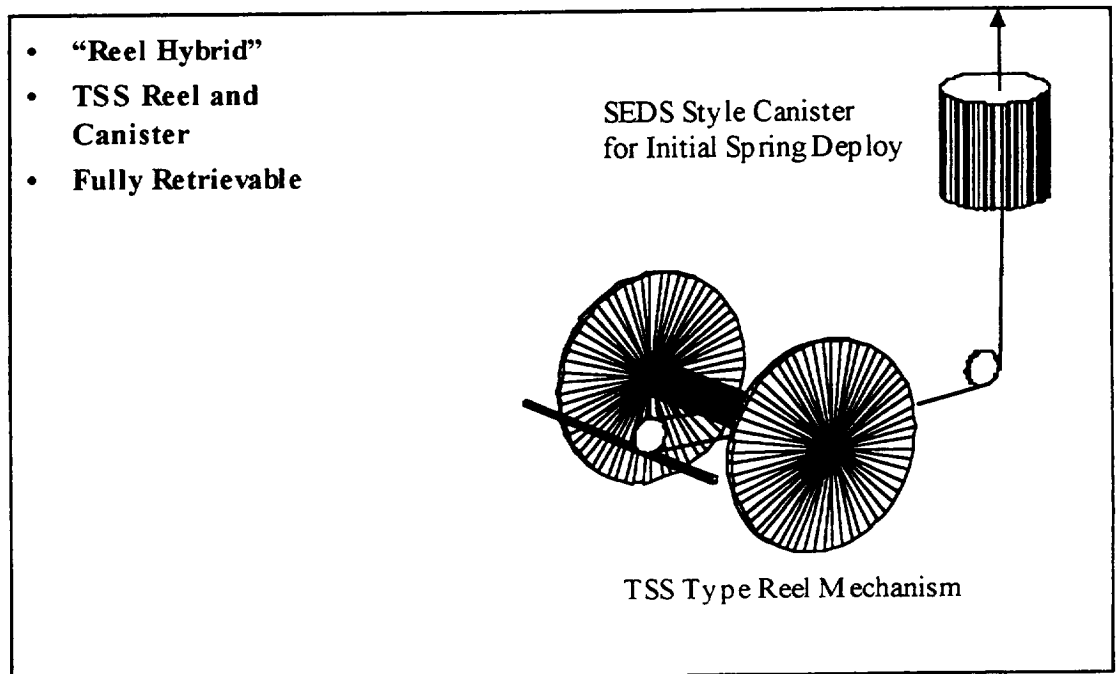


Figure 5 Reel/SEDS Hybrid

3.1.2.2 Other Deployer Considerations

3.1.2.2.1 Deployer Boom

The deployer boom provides an initial separation between the cargo bay of the Shuttle, and provides 12 meters of space in which tether can “pile up” in case of a tether break, thus increasing the time for crew reaction. For a deploy-only system the initial separation may not be beneficial. Additionally, at the higher tensions for this >90 km tether deployment length, the snapback speed is higher than the 20 km TSS-1 tether. The twelve meter boom does not provide much additional crew reaction time for the longer ATM tether. TSS was approved by the JSC Flight Safety Review Panel with the boom in place.

The boom does serve as an inflection point through which the tether can line up with the Orbiter center of mass. This can provide additional operational flexibility in controlling tether system behavior.

For the atmospheric tether mission, the tip shear applied to the boom from a nominal tether tension of 300N is approximately 100N. The maximum Orbiter primary reaction control system (PRCS) load is approximately 350N if all thrusters are fired simultaneously. The existing TSS boom allowable load is 370N. It is

therefore recommended that the boom mast should be reinforced, or PRCS firings must be limited for the atmospheric mission. An improved replacement boom batten set exists. Installation of the improved battens would increase the strength to approximately 540N. In addition, the boom vendor can incorporate improvements developed for recent Space Station booms to further strengthen the TSS deployer boom. These improvements could yield an additional 50 % in strength.

3.1.2.2.2 Flyaway

An initial flyaway technique must be provided to deploy the satellite a sufficient distance for the gravity gradient tension to be greater than the deployer drag forces. Three methods for initial flyaway of the satellite from the Orbiter have been proposed. One is satellite propulsion as used in the TSS, another is spring ejection as with the SEDS, and the third makes use of Orbiter maneuvering.

Providing satellite propulsion, along with a traction drive at the deployer exit, is the most flexible approach. Deployment may be performed at practically any desired speed and may be stopped, if necessary. Recontact of the satellite with the Orbiter is not a significant issue with this approach. The propulsion system may be a part of the satellite attitude control system as it was for the TSS satellite.

A spring ejection technique is simple from the satellite systems viewpoint. No impact to satellite system operations or packaging volume are required. The spring must be sized to provide enough kinetic energy to overcome deployer friction. This may result in high initial satellite separation velocity and a recontact problem if the tether should jam.

Orbiter maneuvering may include zero tension deployments, backaway maneuvers and centrifugal deployment. These have not been considered as feasible for a manned system with a heavy satellite for safety reasons, but may be worth further consideration in the future.

3.1.2.3 Recommended Concept Based on Requirements

A decision tree (Figure 6) was used as a tool to help determine the recommended deployer design. The primary issue is whether a flyaway propulsion system is present on the satellite. If yes, then either a spool or a reel deployer would work. If no, then a spring ejection system must be employed with a spool or a reel hybrid deployer.

The second issue is whether the tether and satellite must be retrieved, either partially or fully with a final docking and relatching of the satellite to the deployer. If this is desirable, then the spool design is eliminated and a reel or reel hybrid is required. If not, then the spool is still feasible.

The third issue is whether the deployment must be restarted to move between the three endmass altitudes of interest during the mission. If yes, then the spool deployer is eliminated due to its friction brake.

It is recommended that a satellite propulsion system be provided for the atmospheric mission. This method has been proven for Orbiter operations and approved by MSFC safety representatives and the JSC Payload Safety Review Panel. This approach offers the greatest operational flexibility and avoids recontact issues of the estimated half metric ton satellite with the deployer/Orbiter.

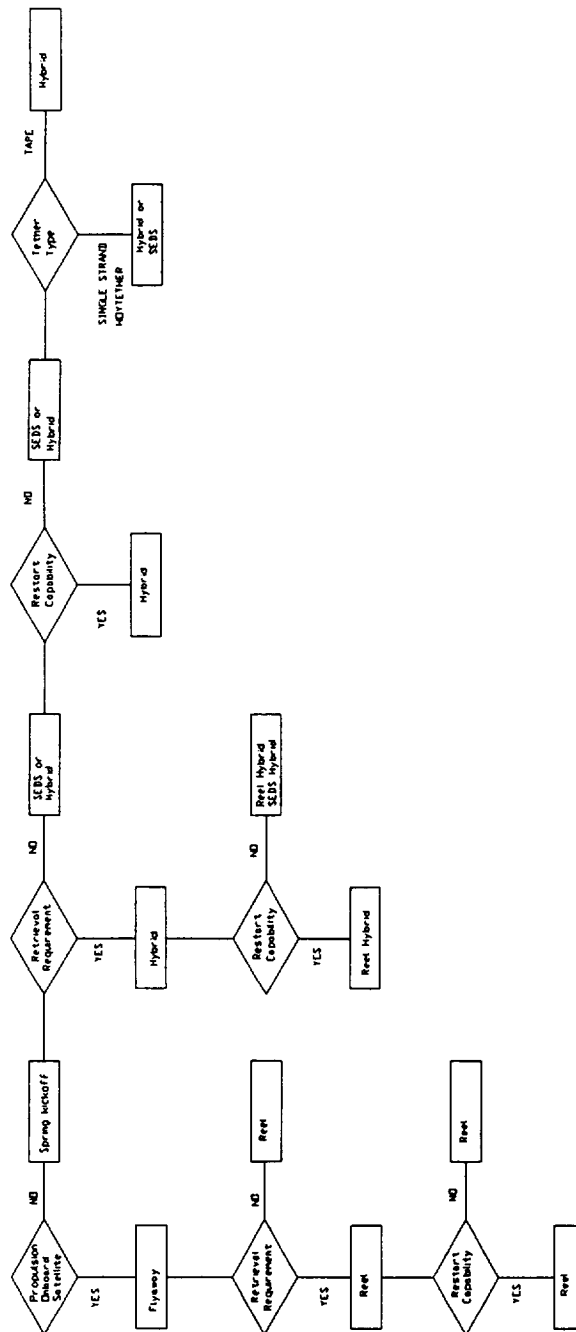


Figure 6 Deployer Decision Tree

A comparison of the three deployer design concepts has been evaluated in terms of the two mission operation scenarios: the baseline scenario which maintains endmass altitude by Orbiter thrusting, and the alternate scenario which combines partial tether retrieval with Orbiter thrusting for altitude control.

For the baseline scenario, any of the three deployer concepts would be suitable.

Due to the restart and retrieval requirements in the alternate scenario, the spool deployers are eliminated from consideration. The hybrid deployer, with an initial spring eject spool is not needed due to the assumed presence of a satellite propulsion system. The reel deployer remains the recommended concept for the alternate mission scenario, as well.

The results of the trade study between the SEDS (spool) and Reel (TSS) type deployers are summarized in Table 2 below. The highest weight factor of 10 was assigned to development needed to comply with ATM requirements. Deployability, flight experience, and complexity were other important considerations.

Characteristic	Weighting	SEDS	Reel
Flight Experience	7	4	6
Development Needed	10	3	8
Orbiter Safety	5	3	9
Schedule	5	5	5
Deployability	8	10	8
Retrievability	3	0	10
Testing	6	5	5
Complexity	7	8	5
Cost	5	4	7
Total		284	386

Table 2 Kepner Trego Analysis of Deployer Options

Recommendation: The TSS deployer is recommended for use on the atmospheric tether mission. It has flight heritage in basic tether deployment operations and it has been approved by the NASA safety community. Relatively few modifications (low development effort) are needed for the existing deployer to assure compliance with the atmospheric mission requirements. These modifications are well understood and considered a low risk to implement.

3.2 Tether System Dynamics Analyses

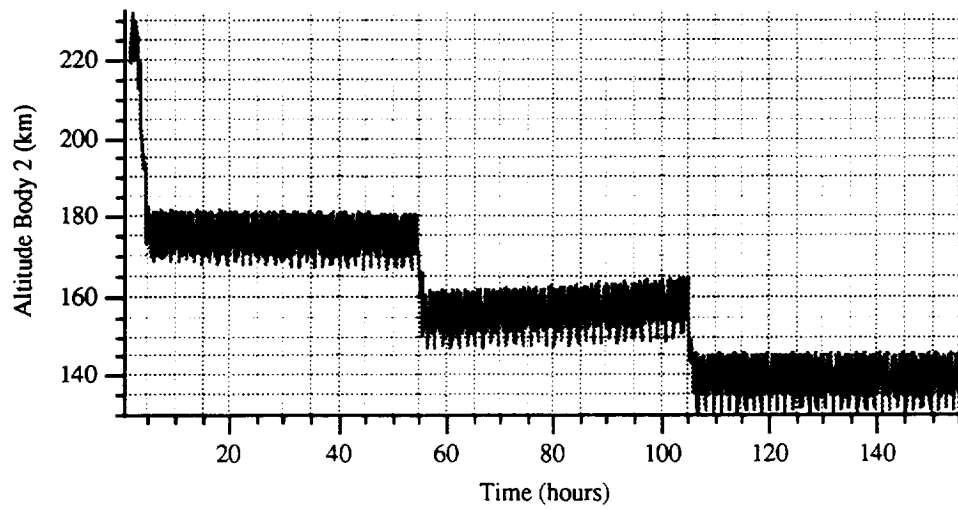
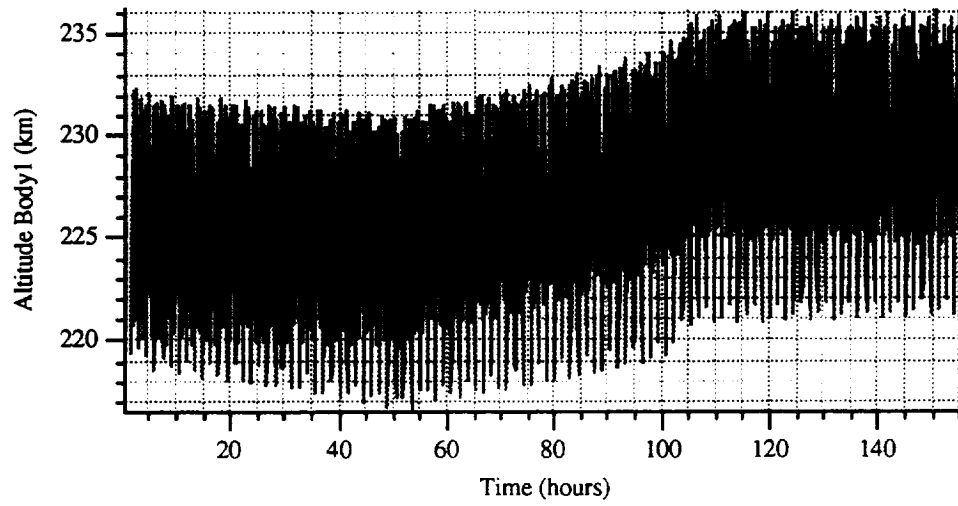
The methodology for deployment of tethers has been developed and validated by the TSS-1 and TSS-1R missions. In addition, the SEDS missions have provided flight experience for spring eject deployments. As a result, this study has not concentrated on the close-in deployment issues, but has focused on satellite altitude management strategies due the aerodynamic dragdown effect on the tethered system.

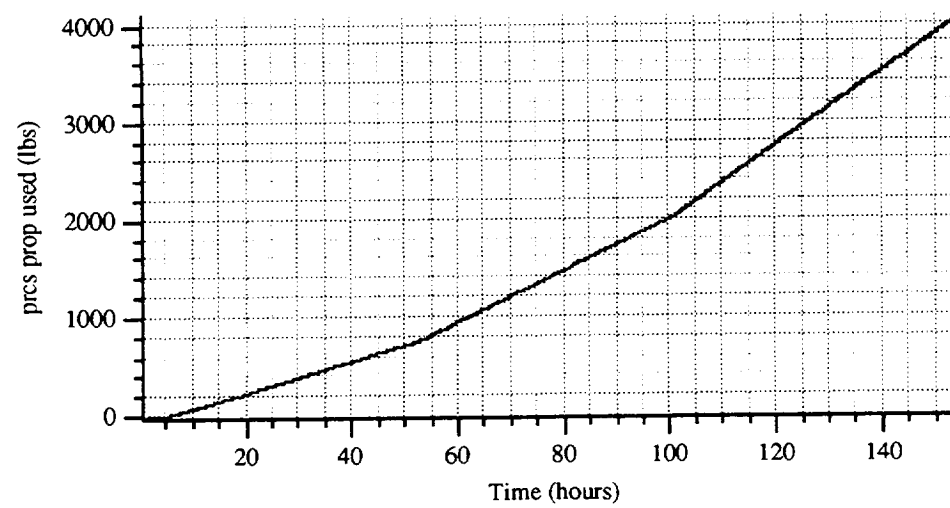
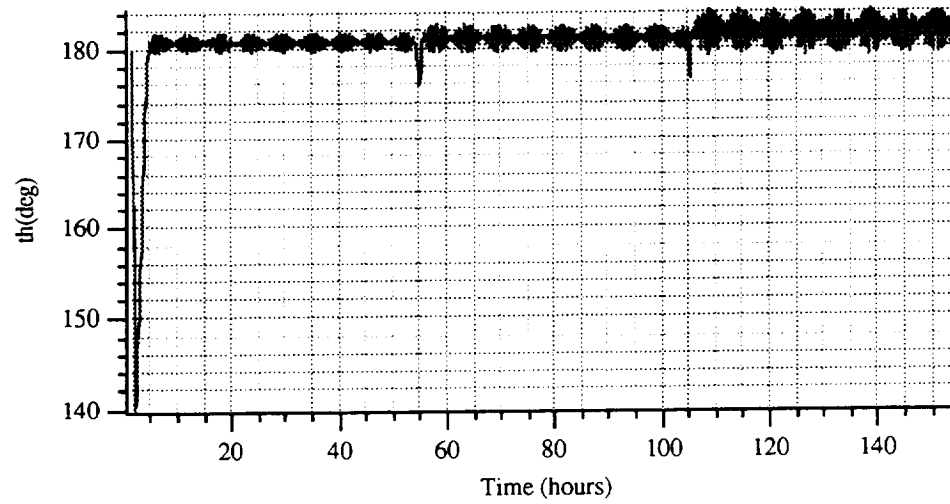
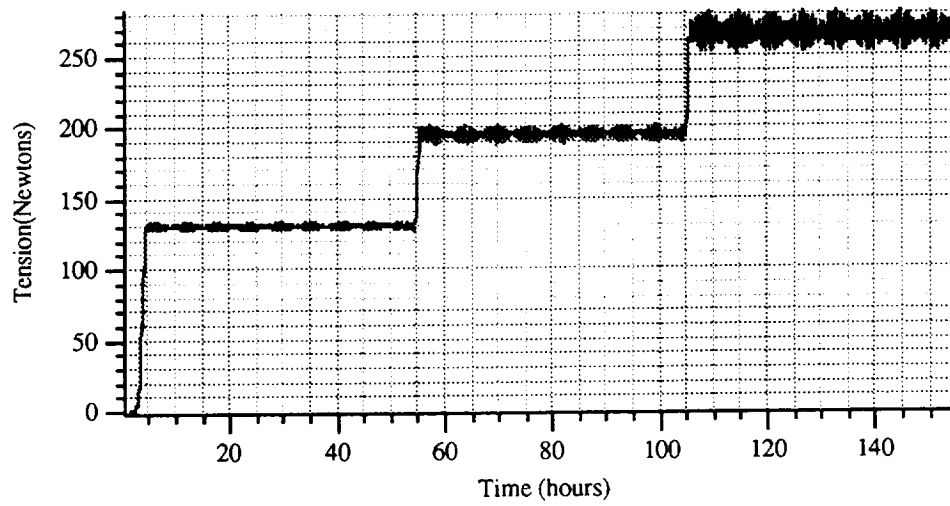
The two basic approaches studied have been to boost the Orbiter with primary reaction control system (PRCS) delta v burns to maintain Orbiter altitude, and to use a combination of tether retrieval and Orbiter reboost to maintain satellite altitude. The second approach has been combined with the first so that a minimum Orbiter altitude of 220 km can be maintained while the satellite is maintained at approximately 170, 150, and 130 km altitudes.

The Orbiter PRCS delta v boosts add angular momentum to the orbiting system and provides a maximum altitude boost on the opposite side of the orbit. The tether retrieval approach reduces the dimensions of the system and directly interacts with the satellite altitude. During Orbiter boost operations, one way to avoid driving the system to an elliptic orbit is to perform the PRCS burns in pairs one-half orbit apart. This strategy, however, can induce some undesired inplane libration. The approach used in this study was to perform the burns based on the libration period of approximately 54 minutes, i.e. the PRCS boost burns would be performed in pairs approximately 27 minutes apart. This approach is expected to work well.

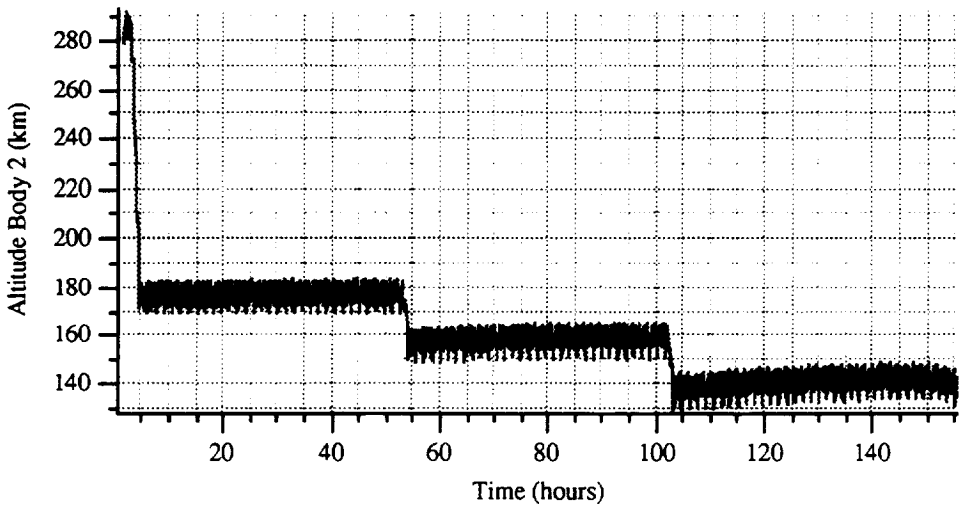
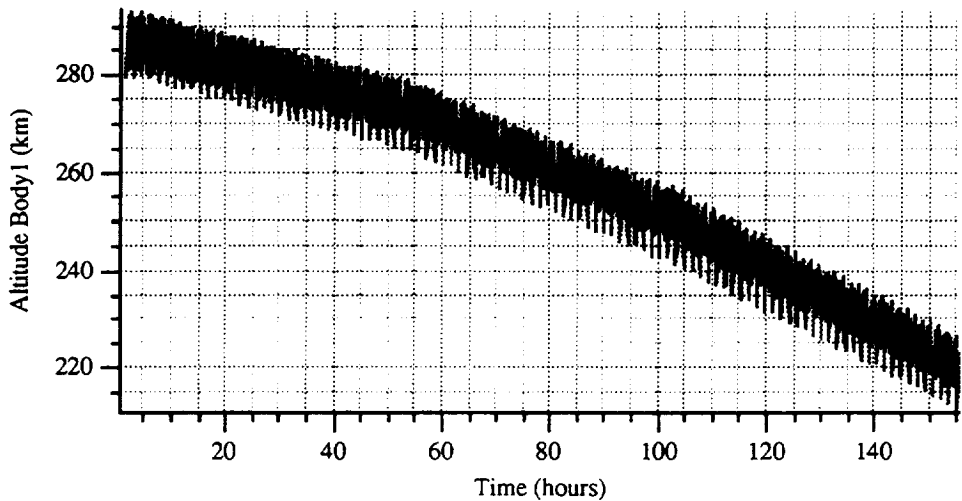
Plots of Body 1 (Orbiter) and Body 2 (satellite) altitudes, tether tension, inplane tether libration angle (θ), and PRCS propellant usage are included below for the two mission scenarios.

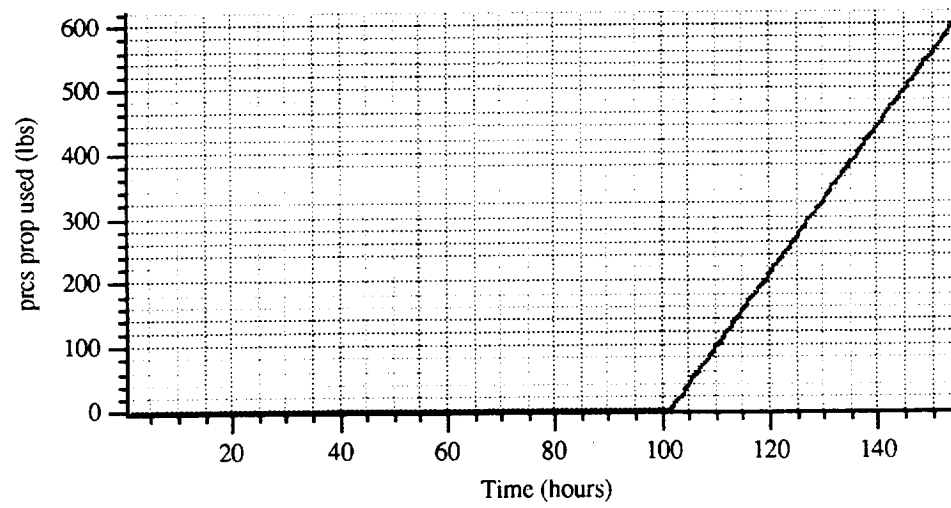
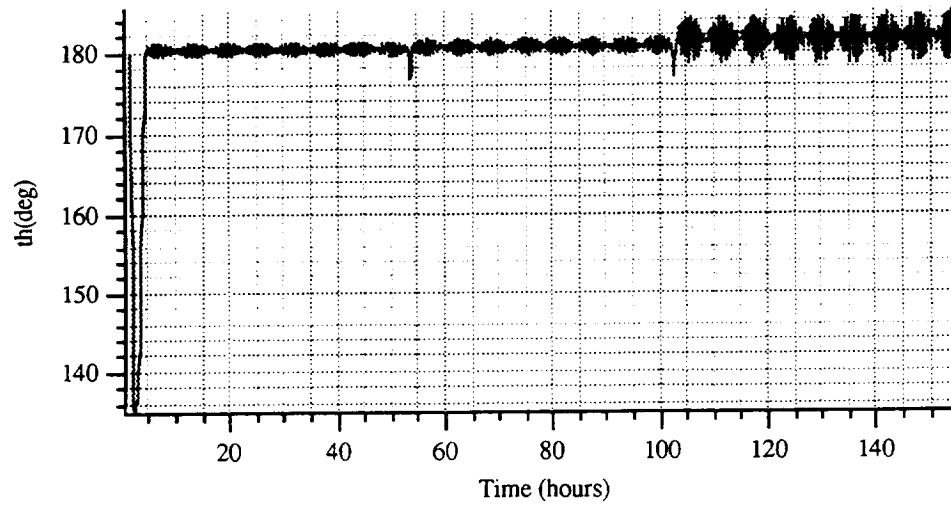
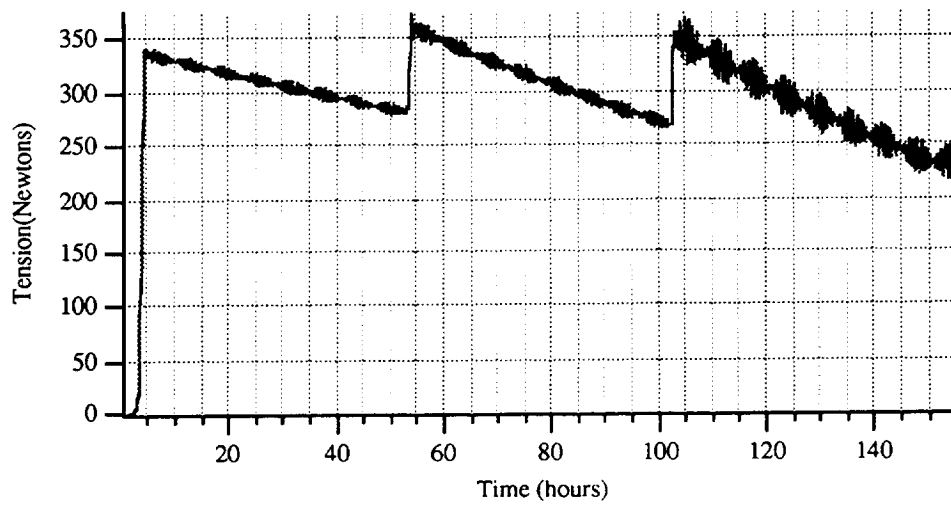
Case 1 Baseline Scenario (Maintain Altitude with Orbiter Reboost)

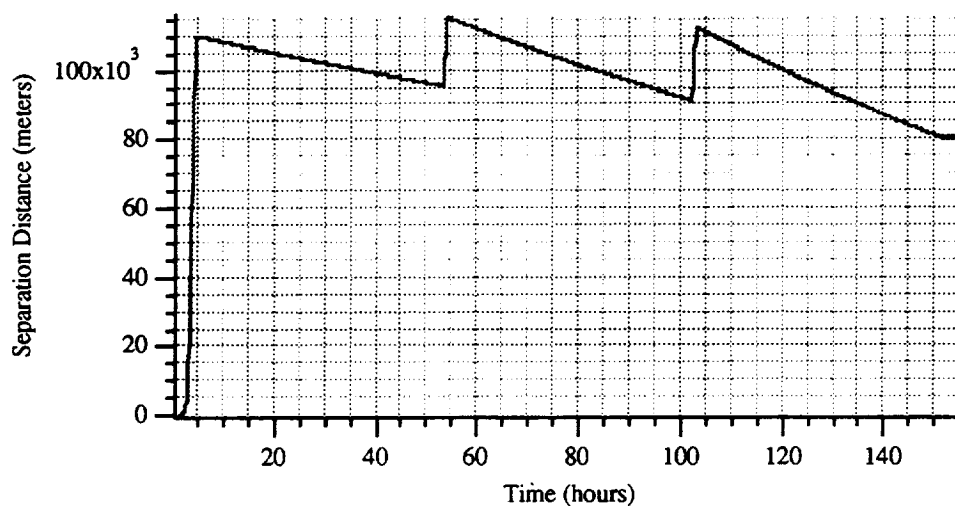




Case 2 Alternate Mission Scenario (Maintain Altitude with Tether Retrieval/Orbiter Reboost)







In summary, the plots above demonstrate that the atmospheric tether mission is feasible from a tether dynamics viewpoint. The propellant usage plots indicate that a significant amount of propellant (> 4000 lb.) is required for the Orbiter reboost operations. Use of the TSS deployer partial retrieval capability provides an attractive option for Orbiter fuel savings (estimated 600 lb. fuel expenditure). The propellant usage figures cannot be directly compared, due to different system altitudes used in each case, but it has been demonstrated that fuel savings can be achieved with the second scenario. In addition, the partial retrieval approach adds operational flexibility. For example, if unexpected atmospheric conditions/turbulence is encountered during the mission, the flight crew can use the deployer manual pulse width commanding approach to retrieve tether and rapidly change endmass altitude. Furthermore, the TSS deployer was designed to receive ground crew commands during the mission. This enables the mission control center to uplink new mission profiles as needed to react or compensate to varying mission conditions.

3.3 Technology Requirements

TSS Reel Deployer: Several low risk modifications are required for the TSS deployer to meet the ATM mission requirements. The modifications are described in the paragraphs below.

The reel motor was originally qualified only for 13 amp continuous motor current (27 N-m) shaft torque. For the tension levels anticipated with the atmospheric mission, it would be expected that the torque requirement would be significantly higher. In this case, the motor and its drive electronics would require requalification. If the required output torque exceeded an (estimated) 40 N-m level, a new motor design (with modified winding encapsulation design and integral cold plate) would be required. The motor drive circuit would require new power diodes because of limits of the existing diodes junction/case thermal coupling. The replacement diodes would require a small development effort; recent new power device packaging methods have made this feasible. The drive electronics would also require new Hall effect current sensors. These are considered standard devices in the required range.

Load cells in the lower tether control mechanism (LTCM) and upper tether control mechanism (UTCM) provide critical tether tension measurements which have been used extensively by ground and flight crews during the TSS missions. The LTCM load cell would require replacement as the existing device does not have the requisite range or overload capability. The replacement unit would be an off the shelf device (as was the original load cell) in the requisite range. The UTCM load cell output would be pegged at the higher tensions but is designed and tested to function as required after removal of the expected high loads. If desired, this load cell could, by replacement of one part, be modified to function with a full scale sensitivity of 500 N. In some ways, however, it may be desirable to leave the UTCM design as is so as to get good resolution at the lower outboard tension levels. The LTCM load cell would give reasonably accurate indications of inboard tension at the higher tensions. At high tensions inboard and outboard tensions do not differ by much in a relative sense.

A spring changeout in the brake assembly is needed to make it compatible with the increased reel torque for this mission. This is considered a simple modification. Miscellaneous deployer cable harness wiring changes would also be required; these are well understood and would require minimal effort.

Further analysis is required to determine acceptability of the twelve meter extendible satellite deployment boom. A spare set of boom batten elements have already been built, and could be installed if slight increases in boom loading are anticipated. If the boom loads change significantly, it is recommended that design characteristics that have been developed for Space Station boom applications be used on a replacement TSS boom mast. These Space Station boom designs have been extensively tested and qualified for space flight on a similar mast at the TSS boom subcontractor facility. A final recommendation for boom refurbishment or design modification can only be made after higher fidelity mission simulations and expected flight loads are defined.

General deployer refurbishment and reassembly of the boom canister, LTCM and UTCM are required as a result of the TSS-1R post mission investigation. In addition, several fracture critical parts need to be reanalyzed for possible replacement.

In summary, the TSS deployer modifications required for the proposed atmospheric mission would be limited in scope and of known feasibility. No major new technology development is required. This is not surprising, since the hardware was originally designed to meet the requirements of both the electrodynamic missions (TSS-1 and -1R) and a strawman atmospheric mission.

Spool Deployer: The SEDS-type spool deployer must be scaled from its heritage usage with a light endmass at 20 km total deployment distance, to an approximate 500 kg endmass at a distance of 90 km. This scaling effort is anticipated to require new technology in the spool design and friction/braking system. Heat transfer and friction levels are critical issues that must be addressed in the system braking operation. On a relative basis, significantly more technology development is required for the spool deployer, as compared to the TSS deployer modification effort.

Reel Hybrid: This design incorporates a spool for initial tether deployment and a reel for controlling long-range deployment operations and retrieval represents a high level of new technology development. This is the least attractive option and has no heritage flight experience.

3.4 Programmatic Estimation

TSS Deployer Cost:

The modification and refurbishment of the existing TSS deployer for the atmospheric tether mission is estimated at \$14.95 million in FY96 dollars on a Rough Order of Magnitude (ROM) basis. This estimate includes a 20% ROM factor and 15% fee. It is anticipated that this contract would be awarded on a cost reimbursable basis.

The estimate includes an engineering core team to support refurbishment, modification and retest activities. Major procurement items include the tether, new boom mast and new reel motor. The tether procurement activity is estimated at \$400K for the fabrication of two each 130 km tethers (one flight unit and one qualification unit). Tether construction would consist of the baseline Kevlar/Nomex design described in section 3.1.1.

Limitations on the estimate are as follows: 1) no mission operations support is included, and 2) deployer reassembly effort is to be performed by KSC technicians, not LMA technicians.

TSS Deployer Schedule:

The period of performance for deployer modification and retest is estimated at 24 months. The tether fabrication activity is estimated to be 12 months in duration (parallel effort with deployer modification and retest).

Other Cost/Schedule Estimates:

The cost estimates for a spool-type deployer and hybrid deployer are expected to be at least two times the TSS deployer estimate listed above. A significant amount of new development, testing and coordination with the NASA safety community would be required. Schedule estimates for these deployer designs are also expected to be longer than the 24 month TSS deployer period by approximately 12 to 18 months.

4.0 Summary/Recommendations

The engineering study addressed three different deployer design concepts and two mission scenarios for supporting a six day atmospheric tether mission. The deployer designs under consideration included reel-type (TSS), spool (SEDS) and a hybrid concept which combined the spool for initial flyaway and a reel for long-range deployment and retrieval operations. Mission scenarios included the baseline approach where Orbiter thrusting was used to maintain endmass altitude, and an alternate scenario which combined partial tether retrieval with Orbiter reboost to manage altitude.

The recommended deployer design based upon multiple evaluation criteria, is the TSS deployer with limited modification. This recommendation offers the most attractive option in terms of flight heritage, lowest cost and lowest overall risk. The modifications required to support the mission are limited in scope and are well understood. This result is not surprising, since the TSS deployer was originally developed to support both electrodynamic and atmospheric tether missions.

Further study is required on developing the optimum means of controlling satellite altitude. The baseline mission scenario, with Orbiter thrusting only, is a straightforward approach, but uses a significant amount of Orbiter fuel (estimated in excess of 4000 lb.). The alternate approach which augments Orbiter thrusting with partial tether retrieval uses an estimated 600 lb. Although, these two numbers cannot be compared directly due to different system altitudes and drag decay effects, it is an indicator that partial tether retrieval significantly reduces Orbiter fuel consumption. In addition, the partial retrieval option yields greater operational flexibility and faster reaction times in endmass altitude adjustment.

The baseline single strand tether design consisting of a Kevlar strength member and Nomex outer jacket is recommended for ATM usage. It is compatible with existing TSS deployer mechanisms and has a large breakstrength safety factor (2892 N breakstrength vs. 400 N maximum flight load). The Kevlar and Nomex materials have flight heritage from the TSS missions and have demonstrated resistance to environmental degradation. Tether survivability for this design is conservatively estimated at > 93% over the six day period, this is considered an acceptable risk compared to the new technology development required for multistrand tethers.

5.0 Appendices

5.1 Telecon Packages/Presentation Charts

5.2 Miscellaneous

- Statement of Work for Research Entitled “Atmospheric Tether Analyses” per Purchase Order H-27245D
- LMA Technical Memoranda

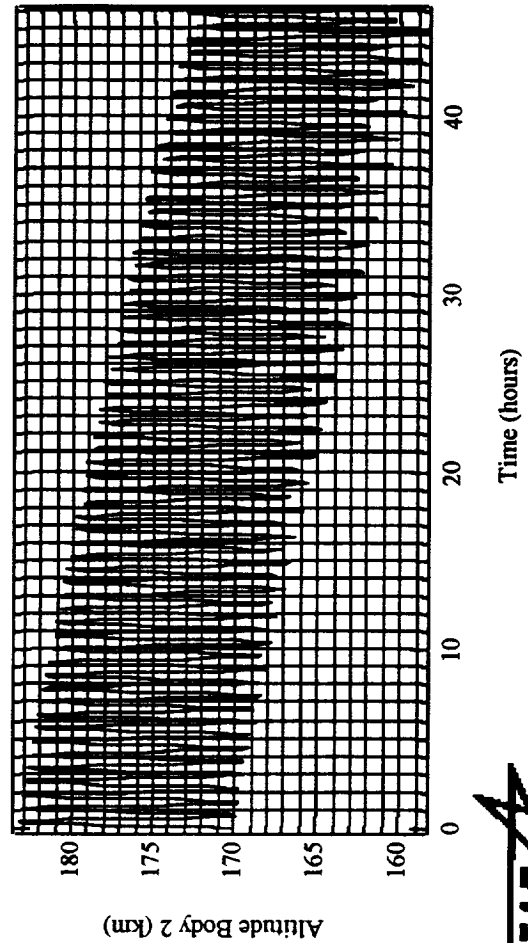
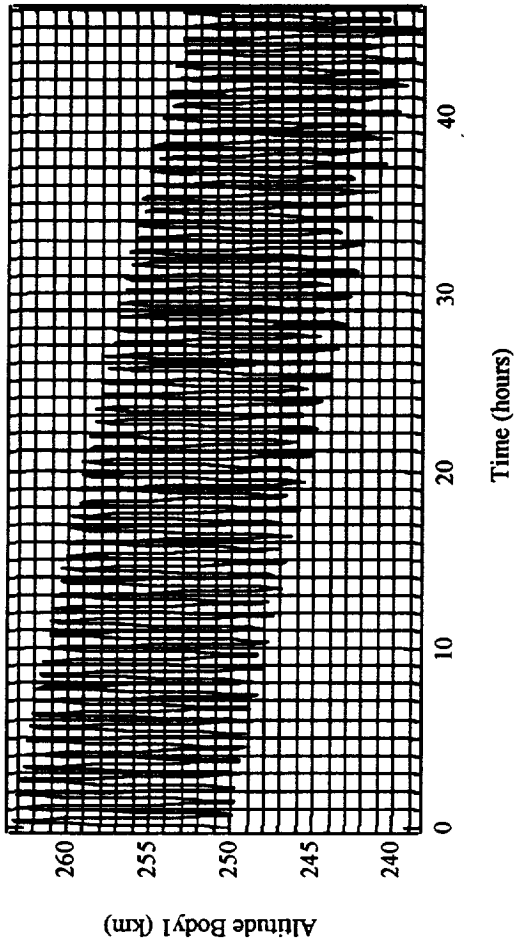
5.1 Appendix - Telecon Packages/Presentation Charts

- Preliminary ATM Profile (8/13/96 Telecon)
- Develop a Requirements Based Deployer Concept (8/27/96 Telecon)
- ATM Mission Tradeoffs (9/10/96 Telecon)

Preliminary ATM Profile

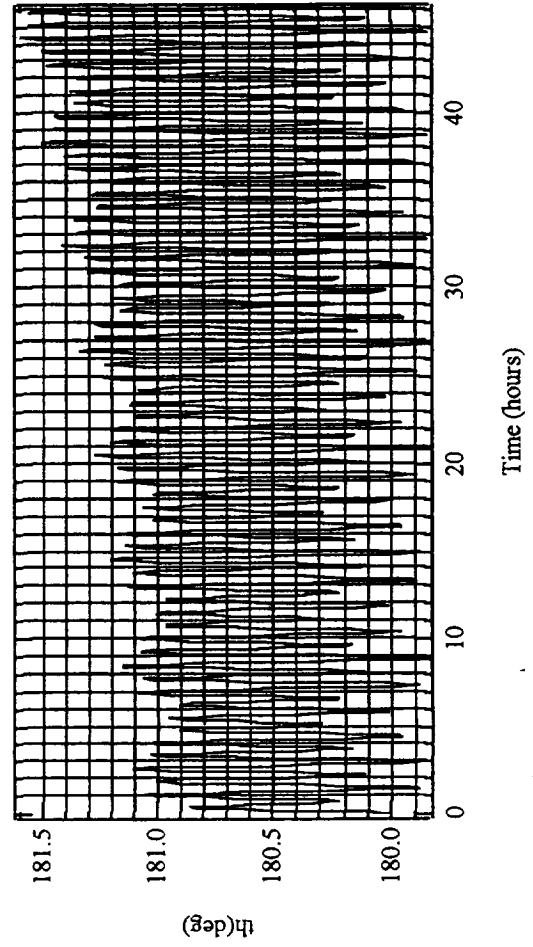
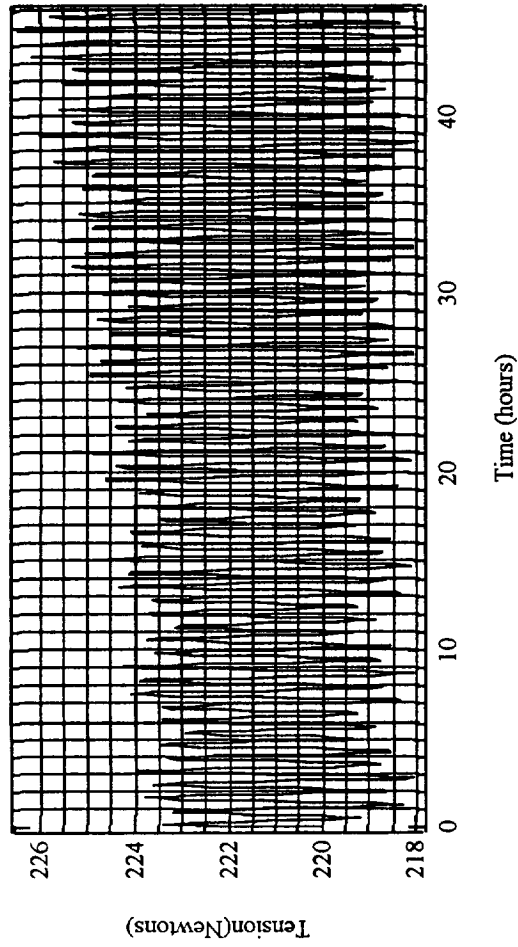
Howard Flanders
Vernon Lunsford

Station 1 Altitudes

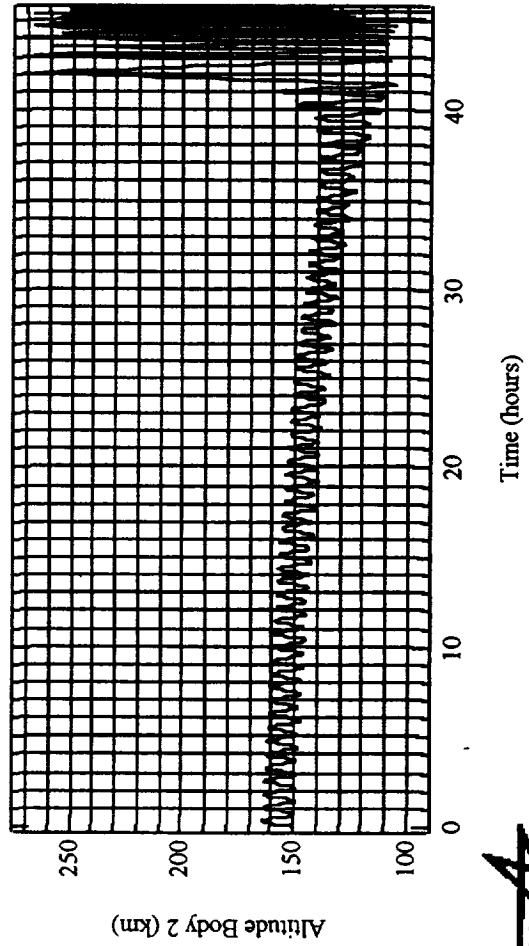
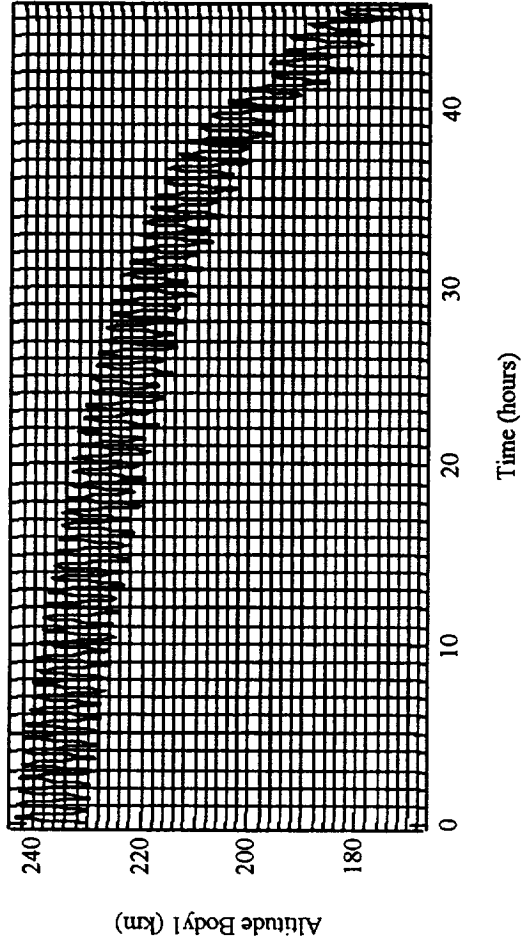


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Station 1 Tension and Libration



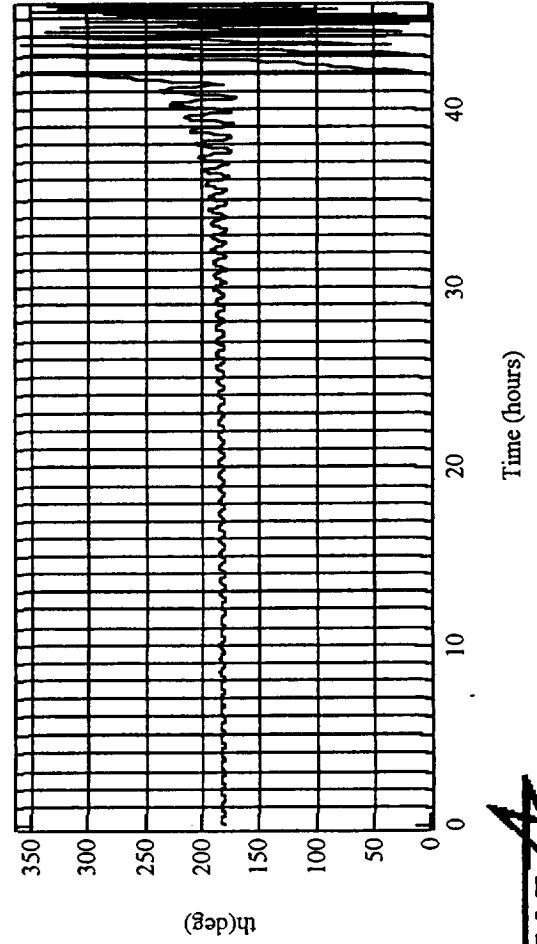
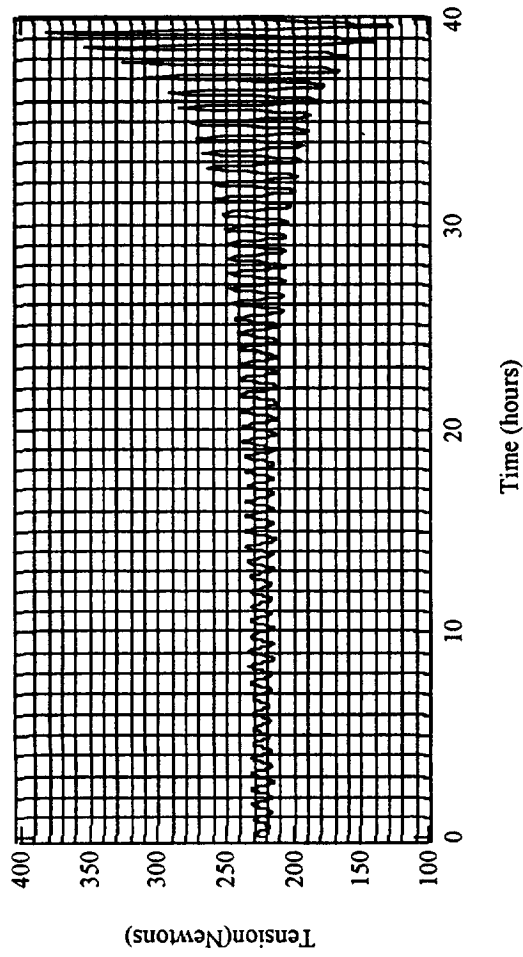
Station 2 Altitudes



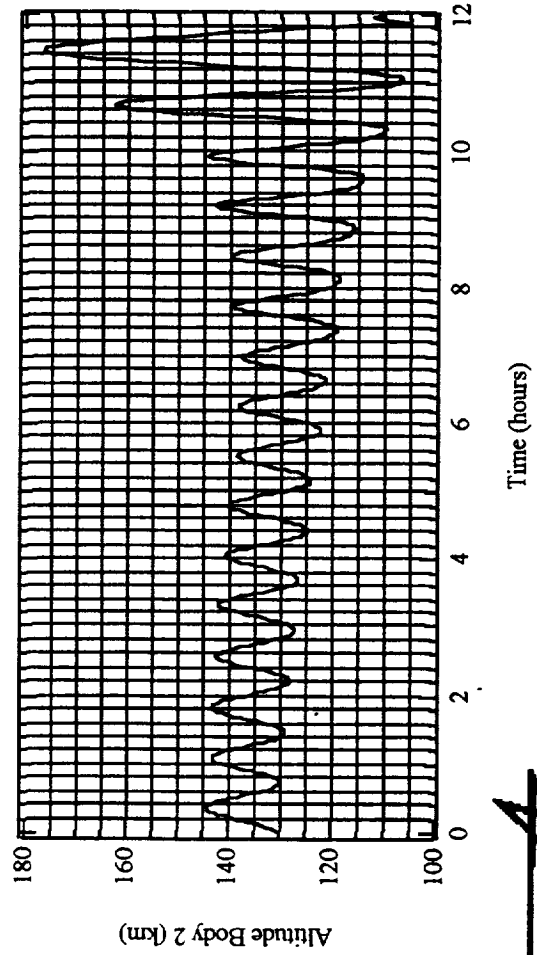
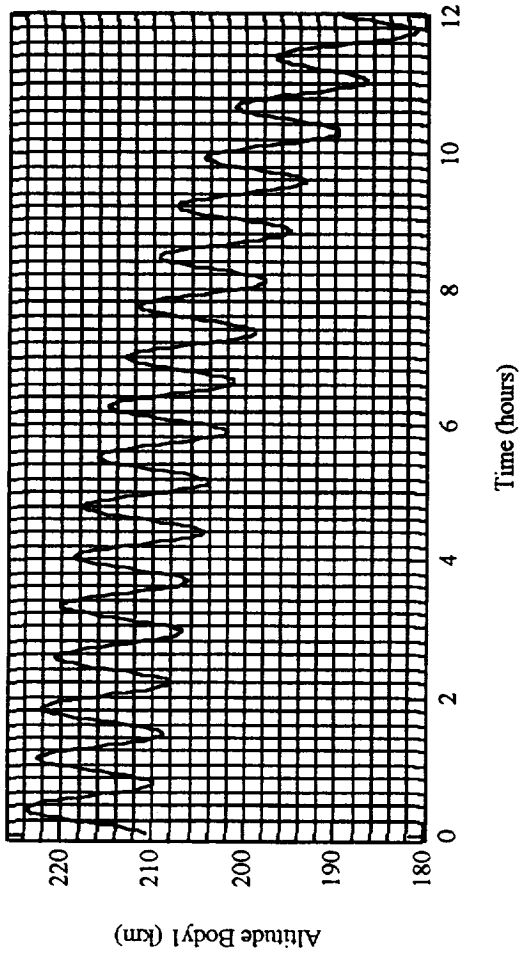
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Station 2 Tension and Libration



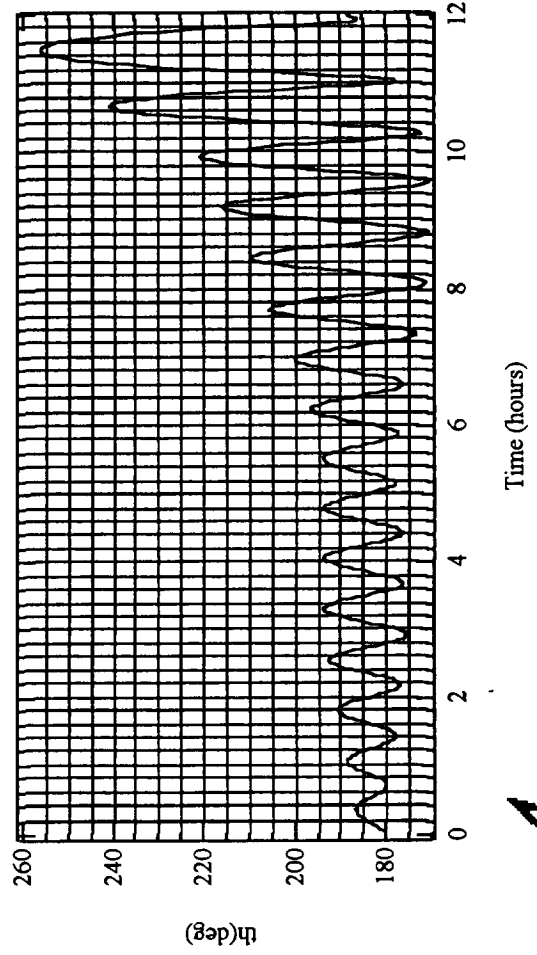
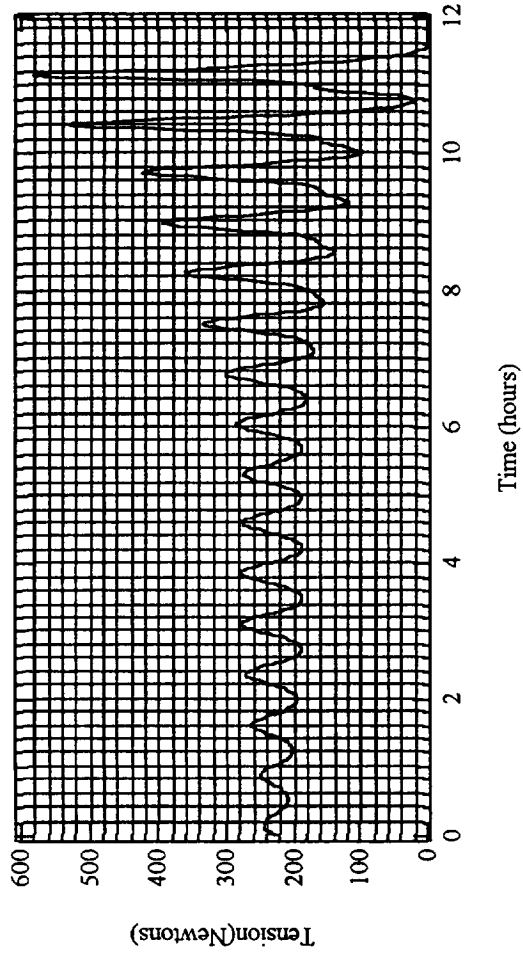
Station 3 Altitudes



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Station 3 Tension and Libration



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Interpretation

- Satellite Altitude Loss Due to Drag
 - 12 km at Station 1
 - 35 km at Station 2
 - 30 km in 37 hrs Then Becomes Unstable
 - 5 km in the Remaining 9 hrs at Initial Decay Rate
 - 69 km at Station 3
 - Extrapolated From Initial 10 km Loss in 7 hrs
- Satellite Begins to Skip When Altitude Falls to 120-115 km
 - After 37 hrs on Station 2
 - After 7 hrs on Station 3
 - Hang angle increases to 75 ° Before Slack Tether Occurs
- Atmospheric Density Not Precisely Known
 - Density Increases Quickly at 120 km in Model
 - Small (10 km) Error Could Drastically Affect Mission

Options

- Reboost Shuttle Only
 - Requires Equivalent of 116 km of Reboost
 - Need to Determine Effect of Perturbations on Deployed Tether
- Retrieve Tether Only
 - Total Tether Deployed Would be Approximately 136 km
 - 116 km Tether Out to Totally Compensate Drag Loss
 - Plus 20 km Tether Deployed at Station 3 to Keep Shuttle Above 150 km

Combination Option

- Combination
 - Reboost for Stations 1 and 2
 - Use Retrieval Capability to Fine Tune for Science
 - Retrieve for Station 3
 - Can Use Retrieval To Fine Tune for Actual Atmospheric Density
 - May Also Need Some Shuttle Reboost
 - Shuttle Final Altitude May be as Low as 150 km
 - Works Out to 90 km Initially Deployed

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Eliptical Orbit

- Fly Eliptic Orbit
 - Dip Into Atmosphere at Ellipse Perigee
 - Less Time for Atmosphere to Perturb System
 - Drags System Down on Apogee of Ellipse, not Perigee

Summary

- Estimated Orbital Decay is:
 - 12 km at Station 1
 - 35 km at Station 2
 - Unstable in 37 hrs
 - 69 km at Station 3
 - Unstable in 7 hrs
- A Combination of Orbiter Boost and Tether Retrieval Appears to be the Most Attractive Option for Meeting Science Requirements


Issues

- Minimum Orbiter Altitude
- Minimum Deployed Tether Length
- Maximum Tether Length
- Reboost Capability of Orbiter

Develop a Requirements Based Deployer Concept

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Comments

- Deployer Style Initially Independent of Tether Type
- Consider Satellite Capabilities and Mission Profile

Does the Satellite Have Propulsion for Shuttle Flyaway?

- Assume No Centrifugal Deployment
- No Propulsion Means a Spring Ejection System
 - Shuttle Safety Must be Considered
 - Manned Platform will Probably Require a Boom
 - Clearance to Shuttle Structure
 - Time for Crew Reaction in Case of Tether Break/Springback
 - How to Spring Eject from a Boom Tip
 - How to Reduce Frictions to Zero Along Long Tether Path
- Propulsion Flyaway Passed Safety Reviews for TSS
 - Proven in Flights off Shuttle

If A Spring Kickoff is Required

- Is There a Retrieval Requirement?
 - For Emergencies or Station Keeping
 - Does Not Mean Relatching
 - No: SEDS or Hybrid
 - Profile Requires Shuttle Reboost to Compensate for Drag
 - Could do Steady Decline Profile with Some Reboost
 - Requires Extensive Reboost at 130 km
 - Yes: Hybrid
 - Combination of Shuttle Reboost and Retrieval to Compensate for Drag
 - Better Station Keeping at Altitudes
 - More Redundant Passes at 170 and 150 km
 - Flexibility to Fine Tune 130 km Altitude

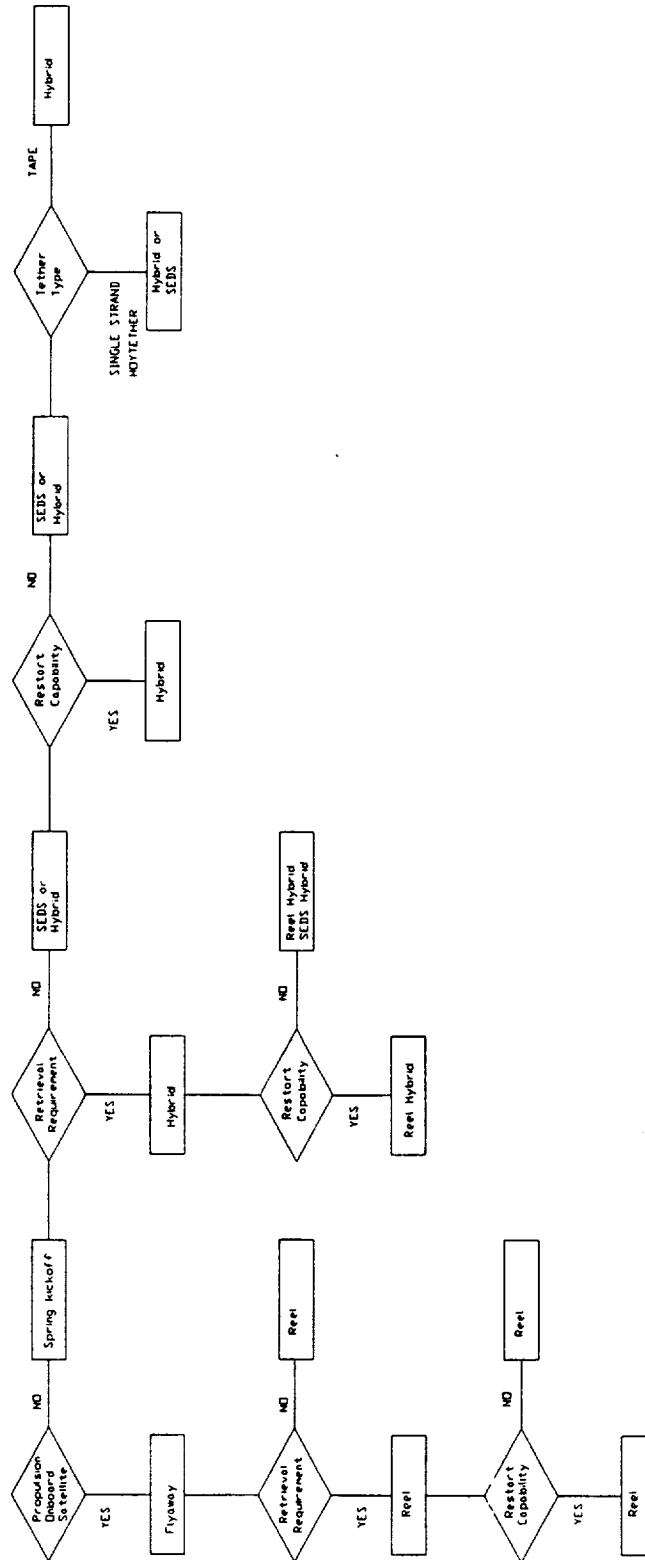
Next, Is Restart Required, Still Spring Eject

- **No: SEDS or Hybrid**
 - Lower Shuttle Altitude to Go to Next Station
- **Yes: Hybrid**
 - Change Altitudes by Deploying More Tether
 - Or a Combination of Shuttle and Deployment
 - Question Restart Capability of The SEDS Capstain Brake
 - Energy Management/Dissipation Issue
 - Tether Wound Around Hot Brake
 - Thermal Effects on Tether
 - Stick-Slip on Startup

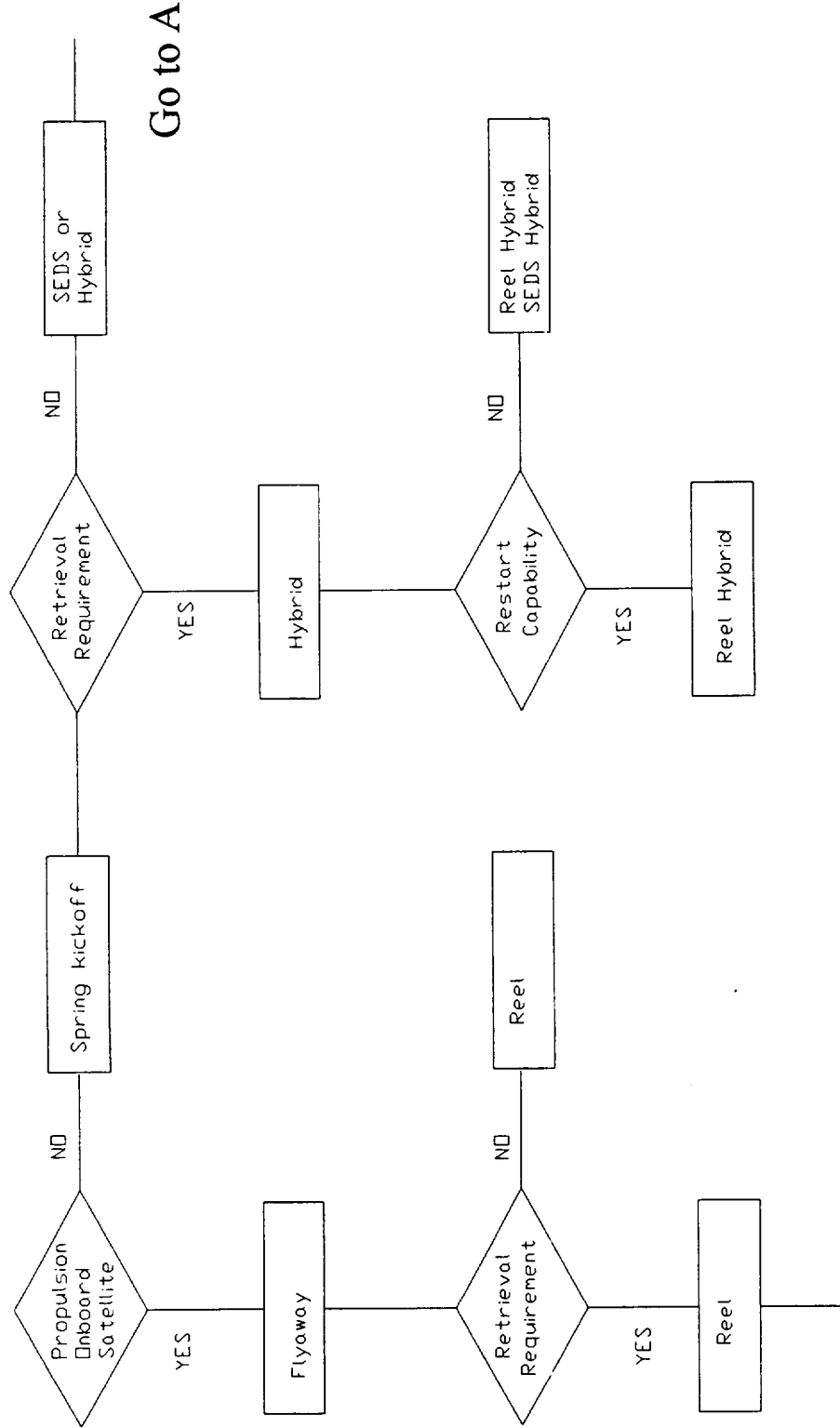
If Satellite Propulsion is Available

- Is Retrieval a Requirement?
 - Does not Necessarily Mean Relatching
 - Could Mean for Station Keeping
 - No: SEDS, Reel, Hybrid
 - Yes: Reel, Hybrid
- If NO, Is Restart Required?
 - No: SEDS, Reel, Hybrid
 - Yes: Reel, Hybrid
- If YES, Is Restart Required?
 - No: Reel, Hybrid
 - Yes: Reel, Hybrid
 -

Decision Tree



Decision Tree for Deployer Choices

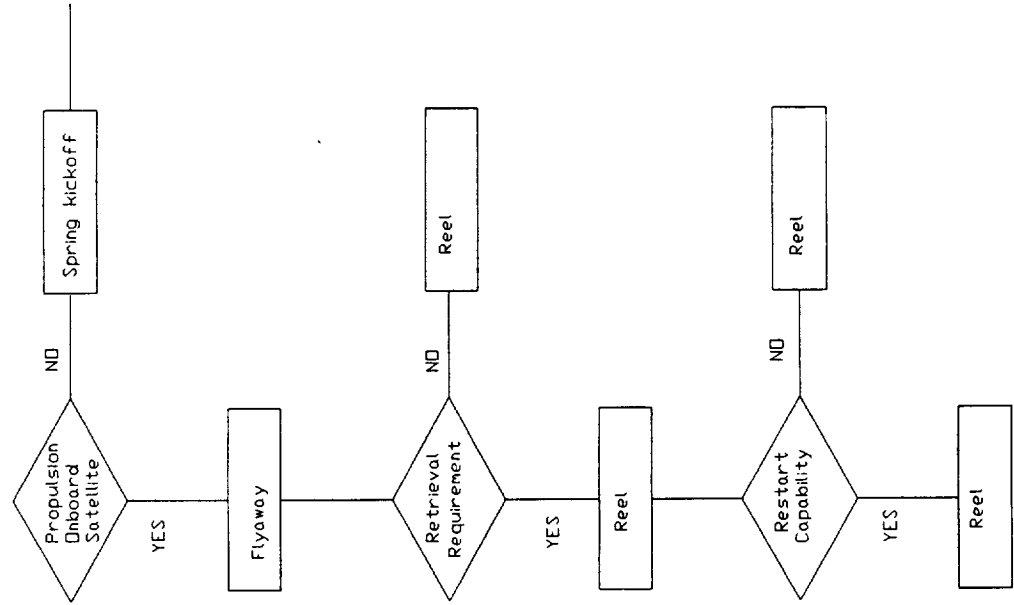


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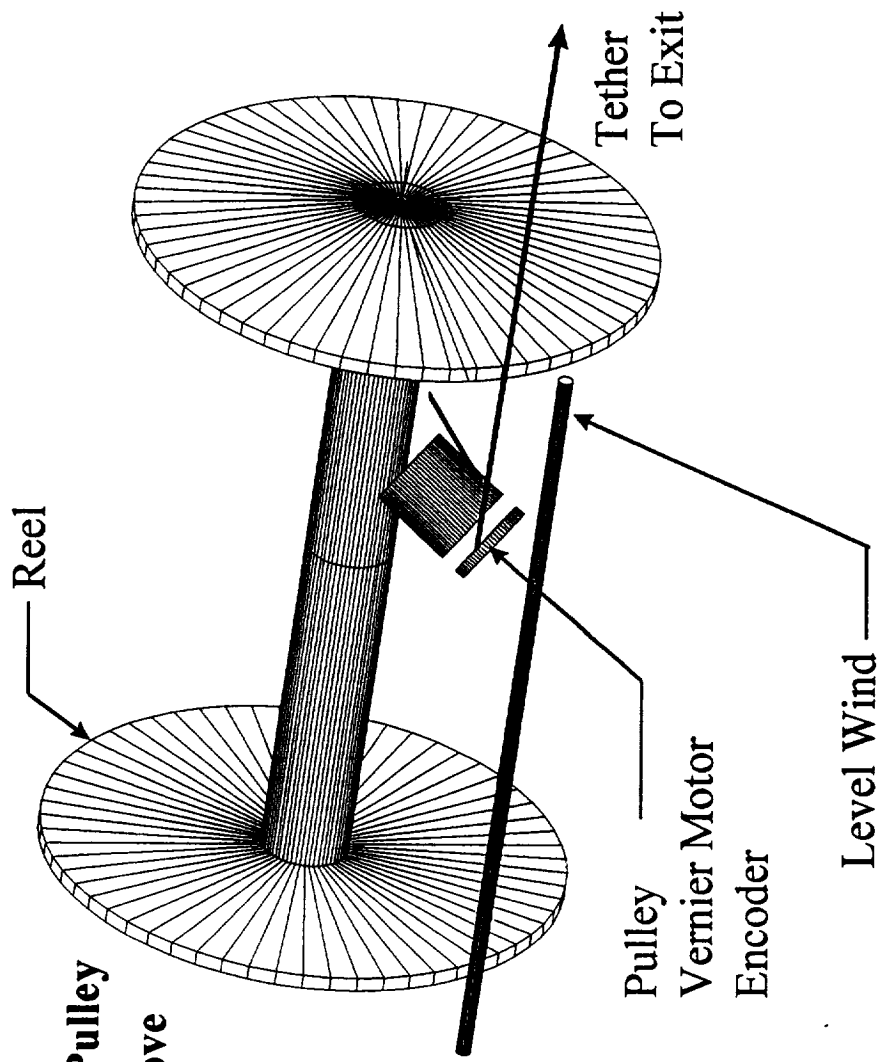
graph TD
    Start([START]) --> R1(( ))
    R1 --> R1D{Retrieval Requirement}
    R1D -- YES --> R1H[Hybrid]
    R1D -- NO --> R1S[SEDS or Hybrid]
    R1S --> R2D{Restart Capability}
    R2D -- YES --> R2RH[Reel Hybrid  
SEDS Hybrid]
    R2D -- NO --> R2H[Hybrid]
    R2H --> R3D{Restart Capability}
    R3D -- YES --> R3H[Hybrid]
    R3D -- NO --> R3S[SEDS or Hybrid]
    R3S --> R4D{Tether Type}
    R4D -- SINGLE STRAND HOYTETHER --> R4SH[Hybrid or SEDS]
    R4D -- TAPE --> R4T[Hybrid]
  
```


Satellite with Propulsion



A Hybrid Reel to Deploy Tape Tethers or Hoytethers

- Retrievable
- Multiple Wraps on Pulley
- Vernier/Encoder Move With Level Wind
- Tensiometer too?



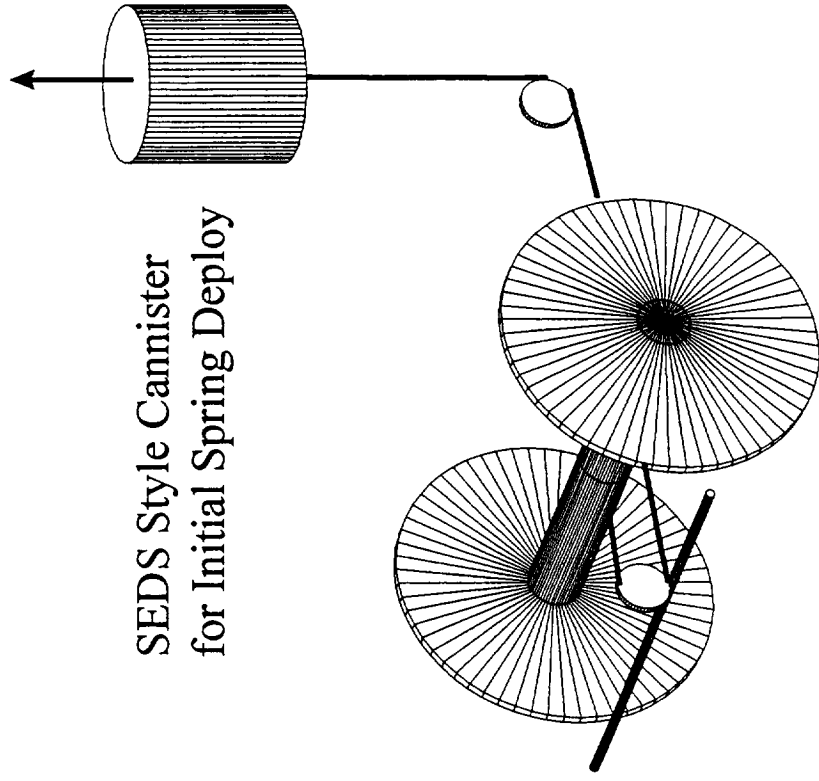
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Another Hybrid Reel for Spring Kickoff

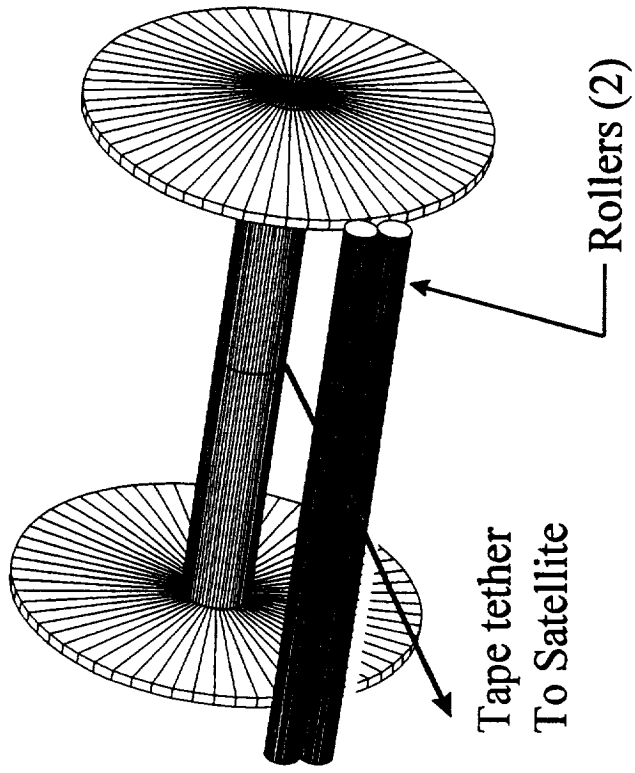
- “Reel Hybrid”
- TSS Reel and SEDS Cannister
- Fully Retrievable



TSS Type Reel Mechanism

A Simple Hybrid Reel for Deploy-Only Tape Tethers

- Motor Driven Rollers
- Friction Brake on Reel
- Encoder on Reel shaft
- No Outboard Mechanisms



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ATM Mission Tradeoffs

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1

Endmass at 170, 150, 130 km for 2 Days Each Using Orbiter Reboost

- Static Deployed Length
- Orbiter Altitude Changed to Move to Next Station
- Simple Deployer, Deploy to >90 km Then be Turned Off
- Tether Spool, Encoder, Tensiometer, Braking Mechanism
- Deployer Boom Optional
- Reel or SEDS

Slow Decay for 2 Days at 170, 150, 130 km. Deploy to Next Altitude

- Requires Restart Capability
- Very Similar to Option 1 for 150 and 130 Altitudes
 - From 150 km Decays to Below 130 km in less than 48 hrs
 - From 130 km Decay to Below 120 km in Less Than 8 hrs
 - Same Orbiter Reboost Required at 130 km
- Requires 100 km Tether Deployed at 130 km
 - Minimum Shuttle Altitude of 220 km
 - Allows for 10 km margin to 120 km
- Tether Spool, Encoder, Tensiometer, Restartable Braking Mechanism
- Deployer Boom Optional
- Reel-Based Deployer

Deploy to Altitude, Retrieve to Maintain Altitude, Deploy to Next Station

- Requires Restart and Partial Retrieval Capability
 - Retrieve Tether at 170 and 150 km
 - 10 km at 170 km Altitude
 - 60 km Deployed
 - 35 km at 150 km Altitude
 - 105 km Deployed
 - Retrieve Tether and Reboost Orbiter at 130 km
 - 70 km Dragdown at 130 km Altitude
 - 160 to 120 km Deployed
- Flexibility to Tune Mission and Revisit Locations
- Tether Spool, Encoder, Tensiometer, Restartable Braking Mechanism
- Deployer Boom Optional
- Reel-Based Deployer Can Do Options 2 or 3 With Few/No Modifications

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Deployer Options

- SEDS Deployer Requires Extensive Scaling to ATM
 - Much Heavier Tether Than Previously Flown
 - More Tension
 - More Energy to Dissipate in Brake
 - Orbiter Safety Issues Unresolved

Kepner-Trego of Deployer Choices

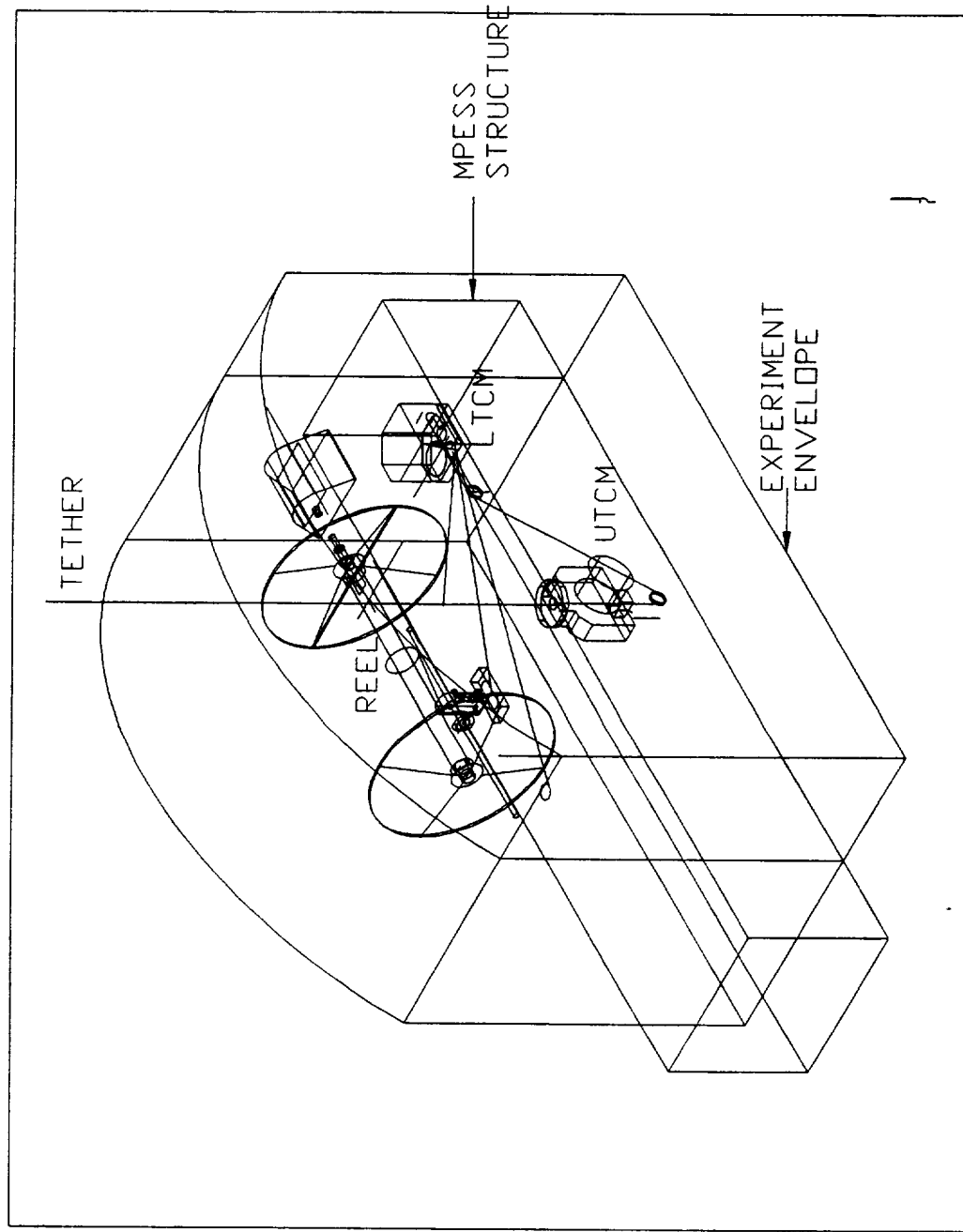
- For Options 2 and 3
- Option 1 Similar Except for “Retrievability”

Characteristic	Weighting	SEDS	Reel
Flight Experience	7	4	6
Development Needed	10	3	8
Orbiter Safety	5	3	9
Schedule	5	5	5
Deployability	8	10	8
Retrievability	3	0	10
Testing	6	5	5
Complexity	7	8	5
Cost	5	4	7
Total		284	386

Deployer Recommendations

- For a Minimum Cost/Quick Mission: Refly TSS Reel Mechanism
 - No Development Required
 - Meets All Requirements of Options 1 thru 3
 - Passed Safety Reviews
 - May Require New Structure and Orbiter I/O Interface
 - Depends on Spacelab Pallet and Smartflex Status
 - Modifications to MCA, and Brake Required
 - Requalify Reel Motor to Higher Currents
 - Could Consolidate/Streamline UTCM and LTCM Based on Boom/No Boom Decision
 - Existing Boom Marginal for ATM Mission
 - Need to Study Effects of PRCs Firings
- Recommend Flyaway Thrusters on Satellite

Reel Deployer in Shuttle Without Spacelab Pallet



5.2 Appendix - Miscellaneous

- Statement of Work for Research Entitled “Atmospheric Tether Analyses” per Purchase Order H-27245D
- LMA Technical Memoranda

ATTACHMENT 1

STATEMENT OF WORK
for Research Entitled
“Atmospheric Tether Mission Analyses”

1.0 Introduction

NASA is considering the use of tethered satellites to explore regions of the atmosphere inaccessible to spacecraft or high-altitude research balloons. Toward this end, a study is being initiated to examine the use of an instrumented endmass tethered to the Space Shuttle Orbiter for atmospheric studies at altitudes between 130 km and 170 km.

2.0 Scope

The feasibility of using an Orbiter based tether system to deploy a scientific probe into the upper atmosphere shall be investigated. A conceptual design for a tether deployer system shall be defined and analyses conducted to determine an estimate of system performance and behavior.

3.0 Contractor Tasks

3.1 Tether Concept Definition

The contractor shall provide an assessment of candidate tether designs for upper atmospheric applications. Analyses/concept-level designs for this application shall include:

- Tether geometry and sizing
- Suggested tether structural material for survival of atomic oxygen erosion, UV radiation, etc.
- Tether tension and loading; break strength requirements, etc.

The contractor shall provide sketches of the design concept(s) showing the dimensions and materials recommended as well as identify possible methods of production and potential vendors.

3.2 Tether System Dynamics Analyses

The contractor shall perform selected tether and tether-related dynamics, mission orbit and profile variation analyses for an upper atmospheric tether mission. Analyses shall include an investigation of the effects of orbital variations (circular vs. elliptical, altitude variations, etc.) and mission profile variations (tether lengths, deployment and possible retrieval profile) on items such as:

A. Mission Profile Design

1. Achievable Mission Duration
2. Deployment and Retrieval Strategies

- B. Deployer Requirements
 - 1. Deployment/Retrieval Rates
 - 2. Tension Profiles (including Orbiter Reboost)
- C. Control Law Requirements
 - 1. Control Strategy
 - 2. Libration Management
 - 3. Impact on Present TSS System
 - 4. Top-Level Endmass Requirements
- D. STS Requirements From Tether Deployment/Operation
 - 1. Reboost Requirement/Impact
 - 2. Libration Management
 - 3. Navigation Impacts/Requirements
- E. Station Keeping Stability
- F. Tether Dynamics Input to Satellite Attitude Control Requirements (pitch, roll and yaw torque)

3.3 Technology Requirements

The contractor shall assess the level of technology required to implement the tether applications defined (with respect to the tether and deployer only). Any technology areas deemed in need of further development shall be identified and quantitative measures of the required development identified.

3.4 Programmatic Estimation

Rough Order of Magnitude (ROM) cost and schedule estimates shall be made for the development of the deployer and tether concepts identified in the study.

4.0 Management

4.1 General

The contractor shall provide regular, informal, technical coordination and communication via telephone and email with the MSFC Study Manager on a biweekly and as-needed basis.

All data, including computer programs, or parts thereof, developed incidental to this study, shall become the property of NASA. A final report (estimate < 15 pages) shall be prepared, documenting the results and trades performed in the study. The report shall be delivered in paper and electronic forms (MS Word compatible) to the MSFC Study Manager. Paper and electronic copies (MS PowerPoint compatible) of all presentation material shall be delivered at the time of informal and formal meetings and reviews.

4.2 Meetings and Reviews

A kickoff meeting, mid-term review and final review of the effort shall take place at MSFC. The contractor shall participate in these meetings and reviews by teleconference.

4.3 Coordination

The contractor shall provide continuing technical coordination and communication with the MSFC Study Manager as described in Section 4.1. The contractor shall coordinate time phasing and technical execution of the study with the MSFC Study Manager and work closely with the MSFC Team. MSFC shall be performing related analyses in an activity complementary to the contractor's effort, thus requiring the close coordination described above.

4.4 Period of Performance

The period of performance for the effort is three months.

Memo

LOCKHEED MARTIN



Date: August 15, 1996
Refer to: TSS-96-RVL-021
To: L. Marshall
cc: D. Doubek, H. Flanders
From: V. Lunsford
Subject: Comparison of aerodynamic drags of Single and Hoytethers

The following is an estimate of the relative aerodynamic drags of equivalent strength single and Hoytethers. Strength is proportional to the filament cross sectional area and drag is proportional to the area perpendicular to the flow. Since both are functions of the diameter of the tether it is possible to estimate the relative aerodynamic drag of the two systems.

A single strand tether should be designed to 4 times the induced load. A Hoytether should be designed to 2 times the induced load. Two Hoytether diagonals should be capable of carrying the load of one of the longitudinal elements. This assumes 100% strength of the longitudinal and diagonal elements at the splices in the Hoytether.

Single strand strength: 4x load

Hoytether strength: 2x load or, for a cylindrical tether:
3 longitudinals @ 2/3 load each
6 diagonals @ (2/3)+2 each = 1/6 load each

Strength is proportional to the cross sectional area.

$A = \pi d^2/4$ A_0 is strength for 1x load
 d_0 is the basic diameter

Single strand tether:
 $4A_0 = A_1$
required
 $4\pi d_0^2/4 = \pi d_1^2/4$
single $d_1 = 2 d_0$

Where:
 A_1 is the cross-sectional area
for a single strand tether
 d_1 is the diameter required for a
strand tether

Hoytether:

longitudinal strands
required

$$2A_0/3=A_2$$

$$2\pi d_0^2/3*4=\pi d_2^2/4$$

required
 $d_2=0.817d_0$

diagonals:
single

$$A_0/3=A_3$$

$$\pi d_0^2/(3*4)=\pi d_3^2/4$$

$d_3=0.577d_0$

where:

A_2 is the cross-sectional area
for a single longitudinal

A_3 is the cross-sectional area
for a single diagonal

d_2 is the diameter required for a
longitudinal

d_3 is the diameter required
for a single diagonal

Drag is proportional to Area= $d*l$

Single Tether:

$$\text{Area} = d_1 l = 2d_0 l$$

Hoytether:

$$\begin{aligned}\text{Area} &= 3d_2 l + 6d_3 l \\ &= 3(.817d_0)l + 6(.577d_0)l \\ &= 2.45d_0 l + 3.46d_0 l \\ &= 5.91 d_0 l\end{aligned}$$

Therefore the ratio of drags is : Hoytether area/Single area= $(5.91d_0 l)/(2d_0 l)=2.96$

The Hoytether appears to have 2.96 times the drag of the single tether.

Vernon Lunsford
Tethered Satellite
(303)977-6956

Memo

LOCKHEED MARTIN



Date: August 30, 1996
Refer to: TSS-96-RVL-022
To: L. Marshall
cc: D. Doubek, H. Flanders
From: V. Lunsford
Subject: ATM Mission Trades

The following is my evaluation of the ATM scenarios:

1. Endmass at 170, 150, 130 km for 2 days each using Orbiter reboost as required.

I assume that this is a static deployer tether length and that the Orbiter altitude will be changed to move to next station.

Deployer: Simple deployer, deploy >90 km of tether then be turned off. Could be a reel, a hybrid, or a SEDS. Still believe that a reel based mechanism is more Orbiter compatible and has lower development costs.

2. Slow decay for 2 days at 170, 150, and 130 km. Rapid deploy to next lower altitude after 2 day period.

The slow decay from 150 km for 2 days will result in the satellite being below 130 km. From 130 km the satellite will be lost in about 8 hrs. So it requires a significant amount of reboost too.

This Deployer must restart, but not retrieve. This is either a Reel or a hybrid. Tether length >90 km.

3. Incorporate a partial tether retrieval for altitude maintenance at 170, 150, 130 km to decrease Orbiter propellant usage.

A reel deployer or reel hybrid. At 130 km requires at least 90 km plus about 60 km tether deployed to compensate for drag.

Vernon Lunsford
Tethered Satellite

